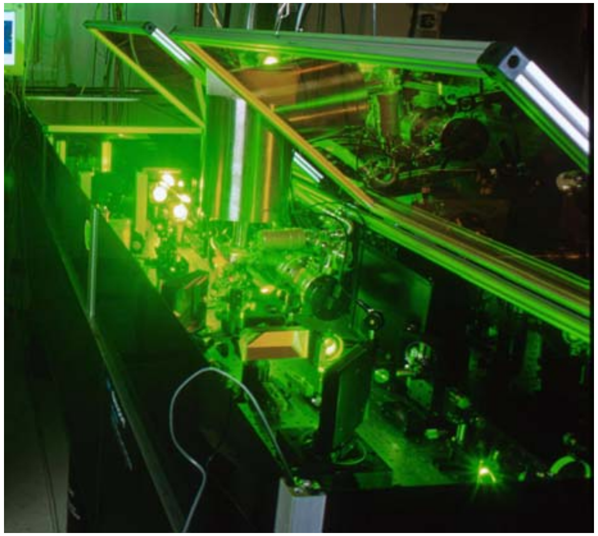
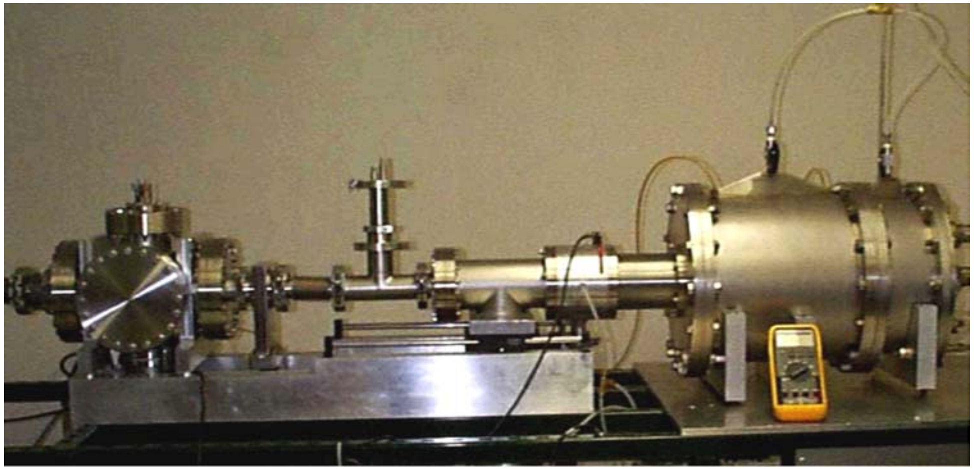
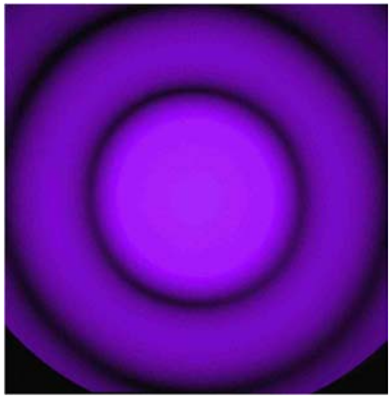
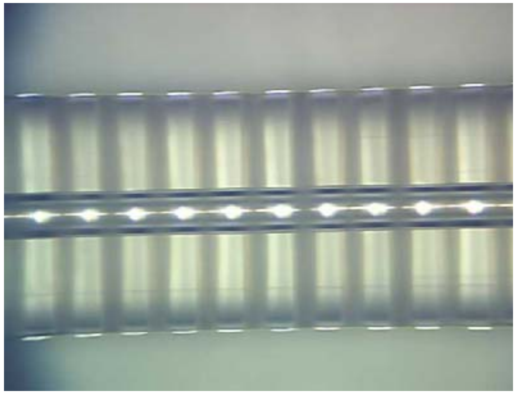
Compact Coherent EUV Sources

Henry Kapteyn, Jorge Rocca, Margaret Murnane









NIST-CU

Outline

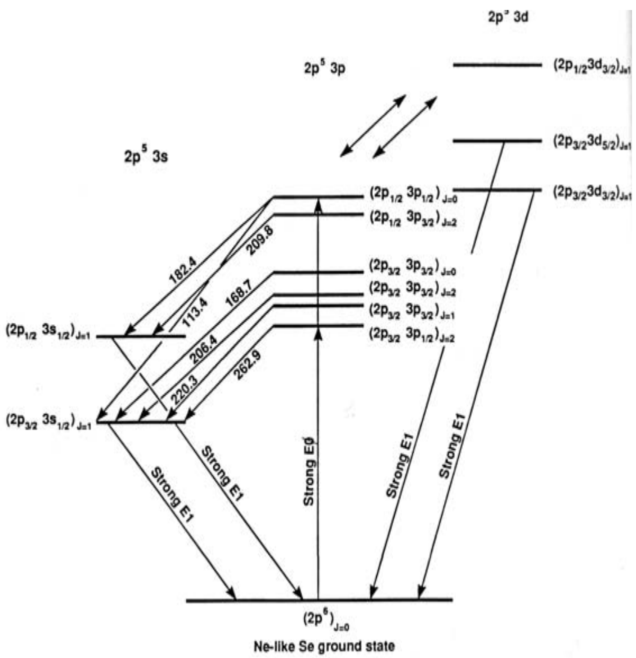
- **Table-top sources in EUV and XUV**
  - EUV laser and high-harmonic sources
  - Current capabilities
  - Future plans for increasing wavelength range and flux in EUV/XUV

- **Applications**
  - Metrology, micro-machining, interferometry
  - Novel linear and nonlinear spectroscopies
  - Ultrafast spectroscopies

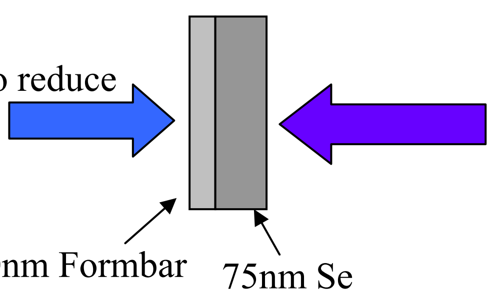
History of EUV laser sources

•**The first EUV lasers were pumped by large lasers and were *single shot***
(Matthews et al. PRL 54, 110 (1985); Suckewer et al. PRL 55, 1753 (1985))

Ne-1



Foil target used to reduce refraction



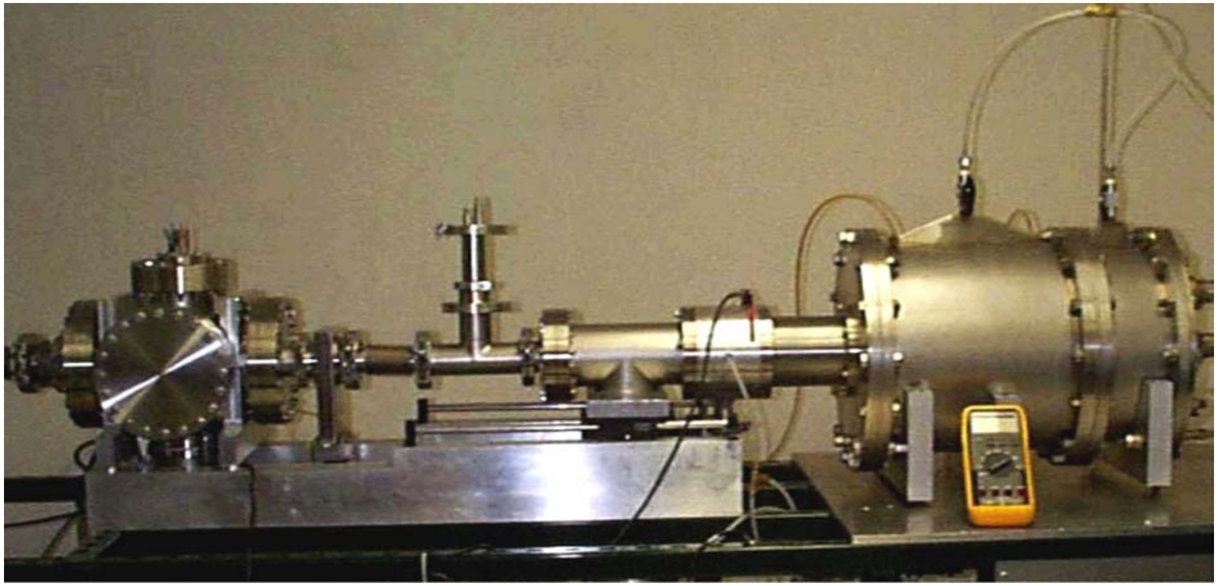
LLNL pump laser characteristics:
Pulse energy= 1 kJ/beam
Pulse duration: 0.45 ns
Intensity: 5×10^{13} W.cm^{-2}

Current EUV discharge-pumped lasers

Ne-like Ar Capillary Discharge Laser : λ=46.9nm

Laser Output Parameters

- Pulse Energy: 0.88 mJ @ 4 Hz
- Average Power $\approx$ 3.5mW
- Peak Power : 0.6 MW
- Pulsewidth : 1.2 - 1.5 ns
- Beam divergence : 4.6 mrad
- Peak spectral brightness : 2×10^{25} ph/(mm^2 mrad^2 sec 10^{-4} BW)



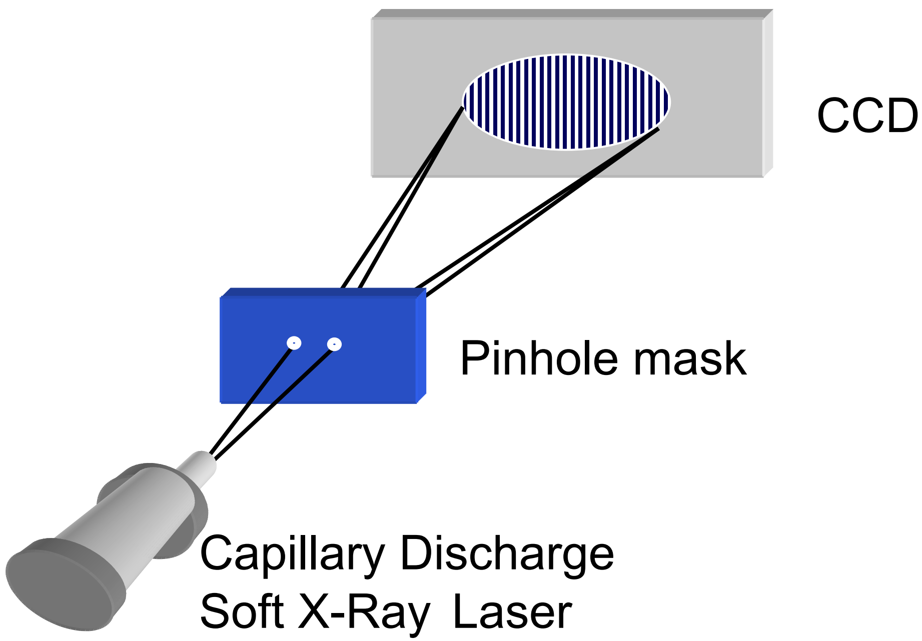
Peak brightness similar to their laboratory-size predecessors. Average powers similar to He-Ne laser!

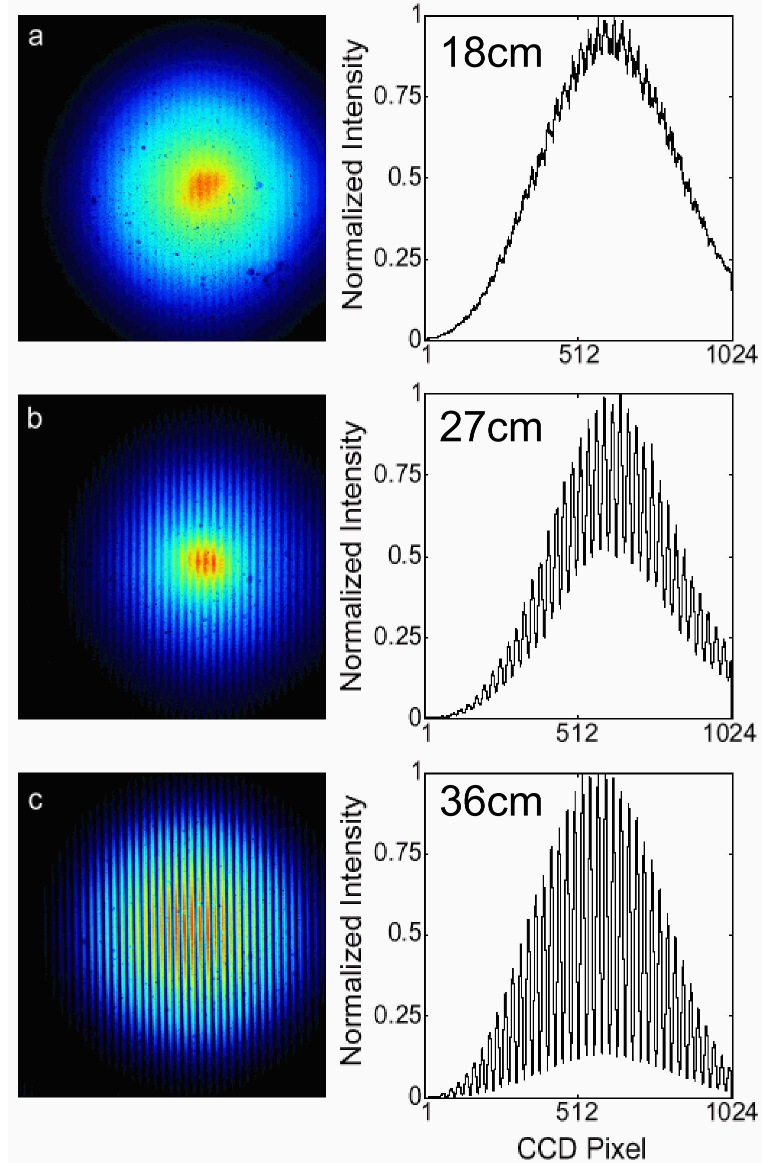
But only at one wavelength!

EUV laser sources are "laser-like"

Characterization of spatial coherence 46.9 nm laser

Two pinhole interference measurements

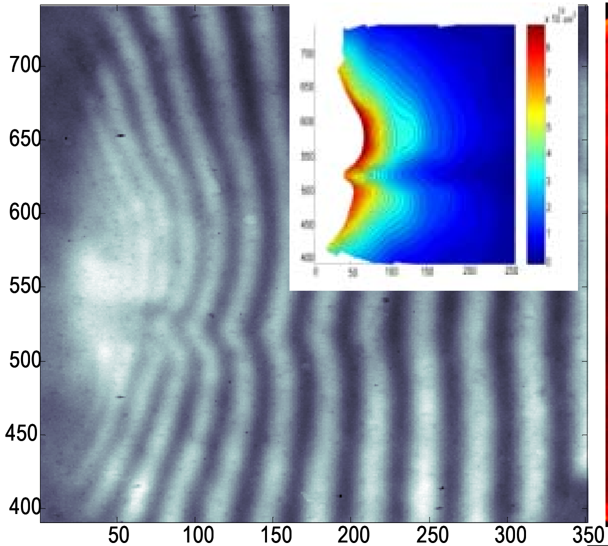


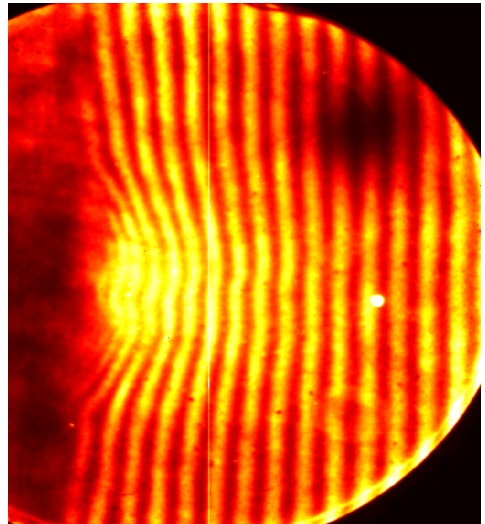


Y. Liu, M. Seminario, F. Tomasel, C. Chang, J. Rocca and D. Attwood. Phys. Rev. A **63,** 033802 (2001)

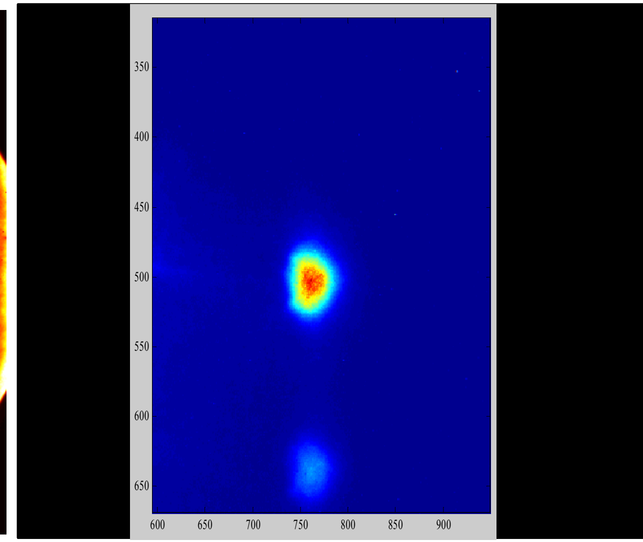
Applications of EUV lasers

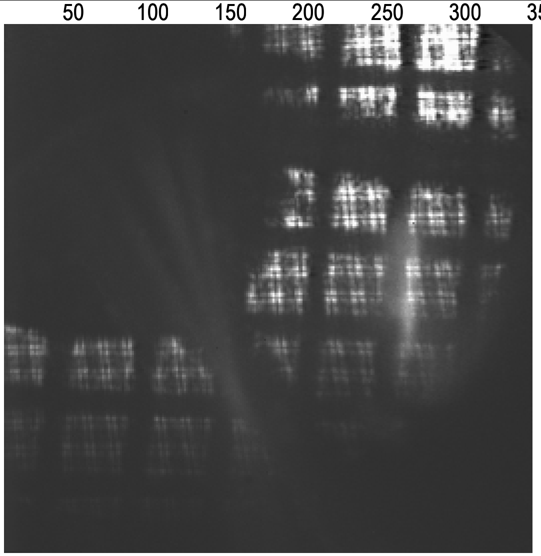
Interferometry of dense plasmas



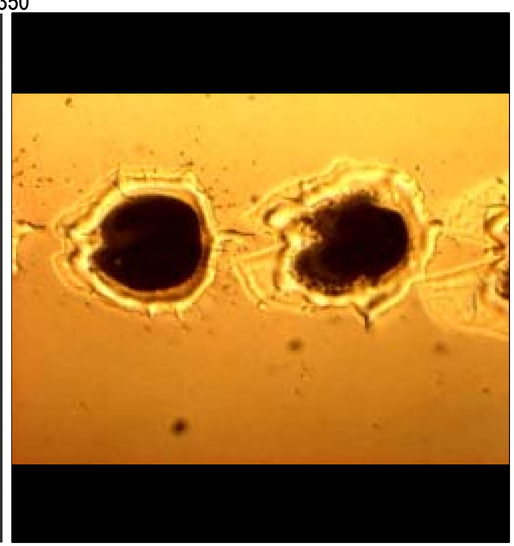


Plasma Generation

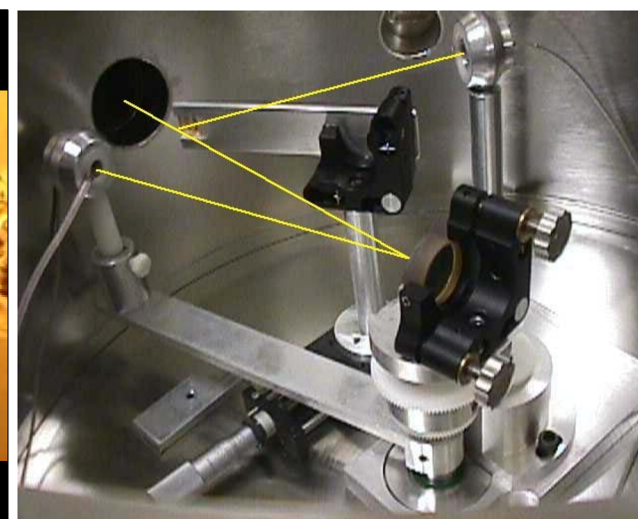




EUV imaging



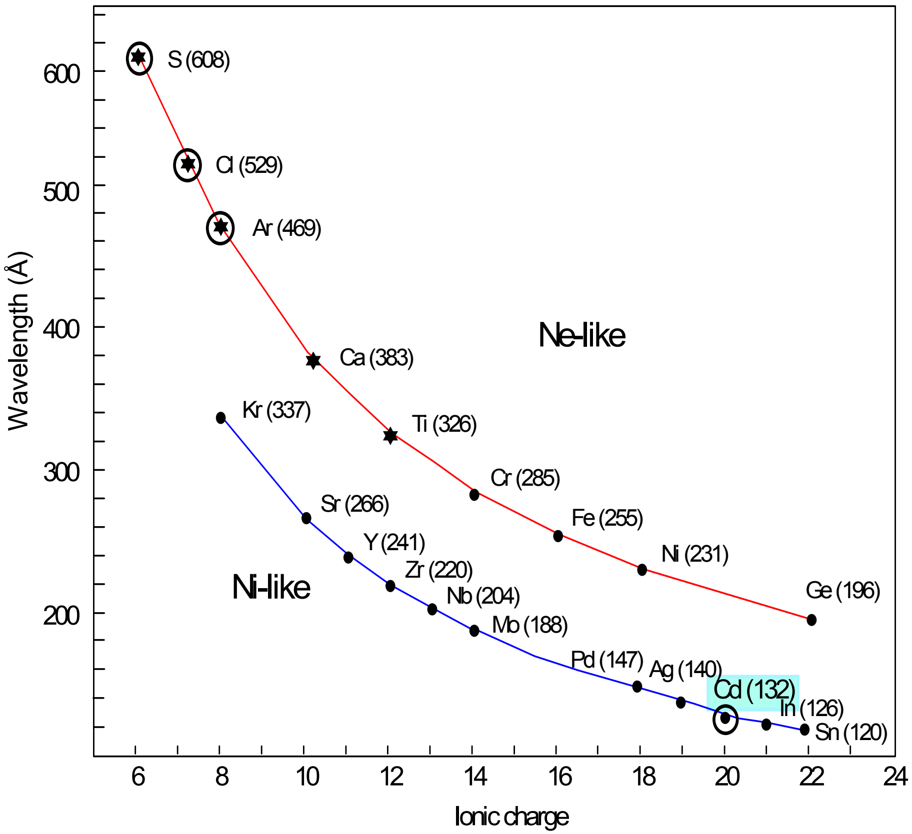
Laser Ablation



EUV optical constants by reflectometry

Scaling EUV lasers to shorter wavelengths

Scaling to shorter wavelengths is more efficient with Ni-like ions

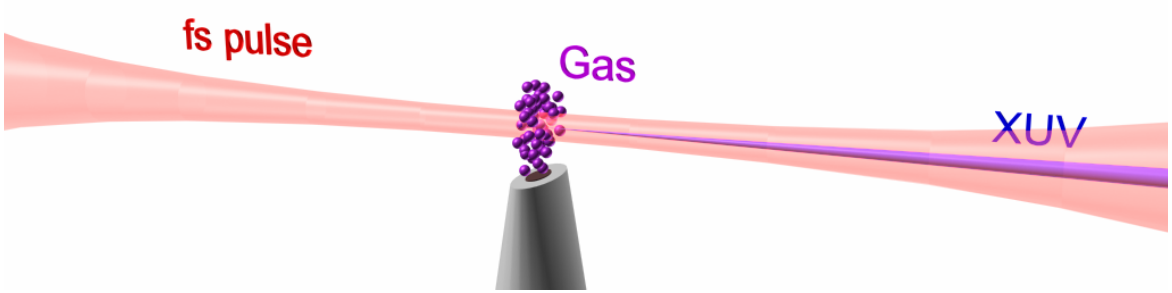


Excitation approaches

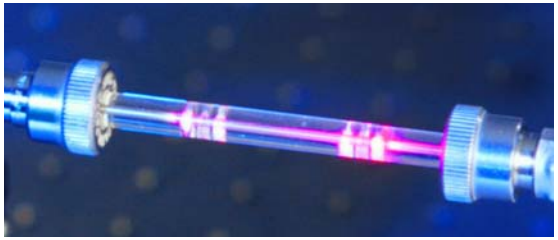
- Extremely fast discharges (>10^{13} A/s current rise time)
- Combined discharges and ultrafast pulse laser excitation
- New approaches to laser-pumped schemes

Extreme nonlinear optics: high harmonics (HHG)

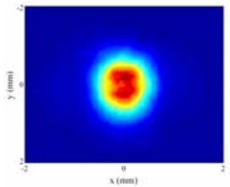
- ***Coherent*** **EUV light is generated by focusing an intense laser into a gas**
- **Broad range of harmonics generated simultaneously from 4.5 - 550 eV**
- **"Laser-like" coherent beams in EUV** (Science **297**, 376 (2002), Nature **406**, 164 (2000))



Gas jet



Fiber

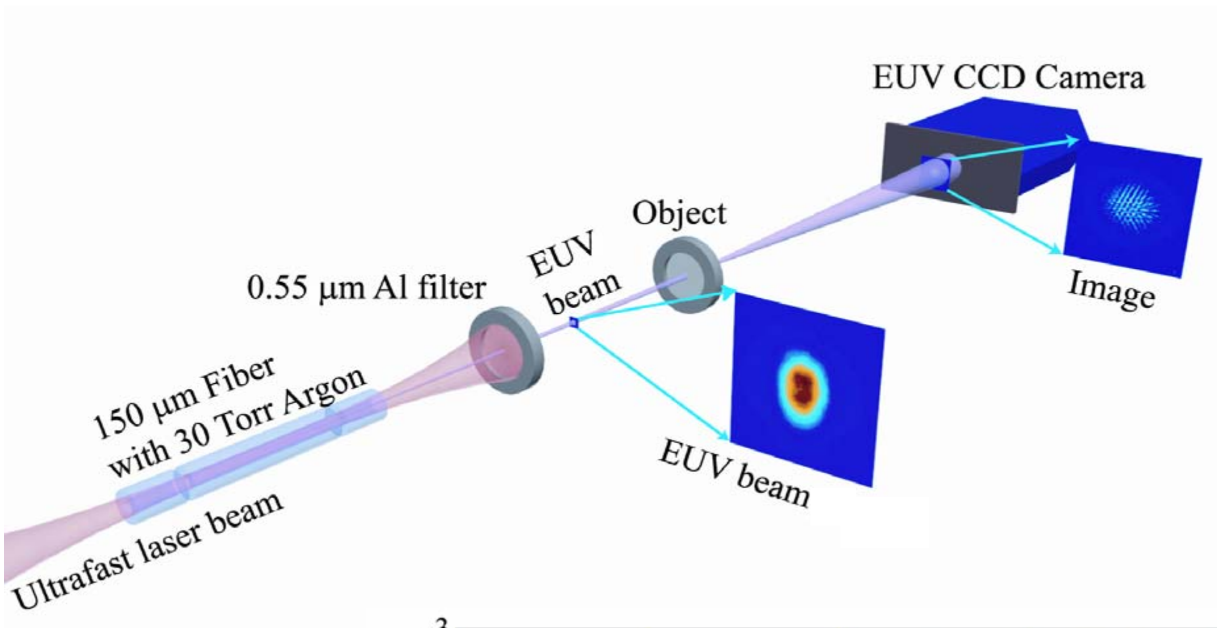


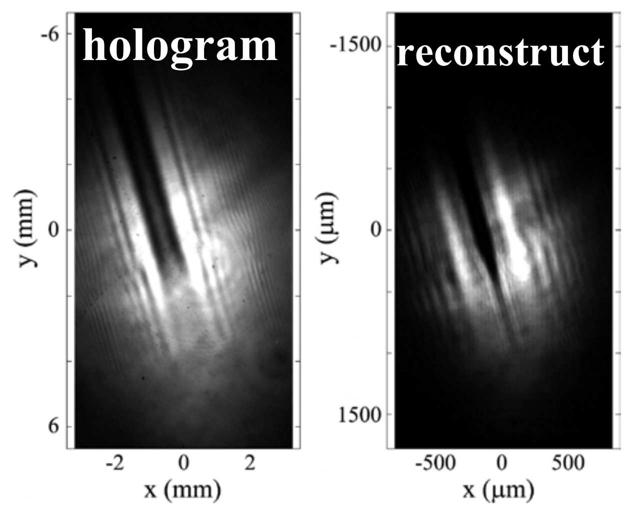
EUV beam

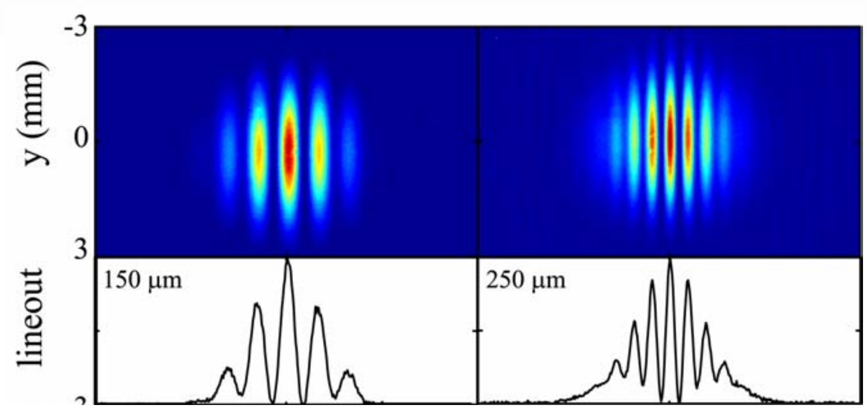
But flux low and tunability limited in UV and VUV!

High harmonic sources are spatially coherent

Opt. Lett. 27, 707 (2002)
Science 297, 376 (2002))

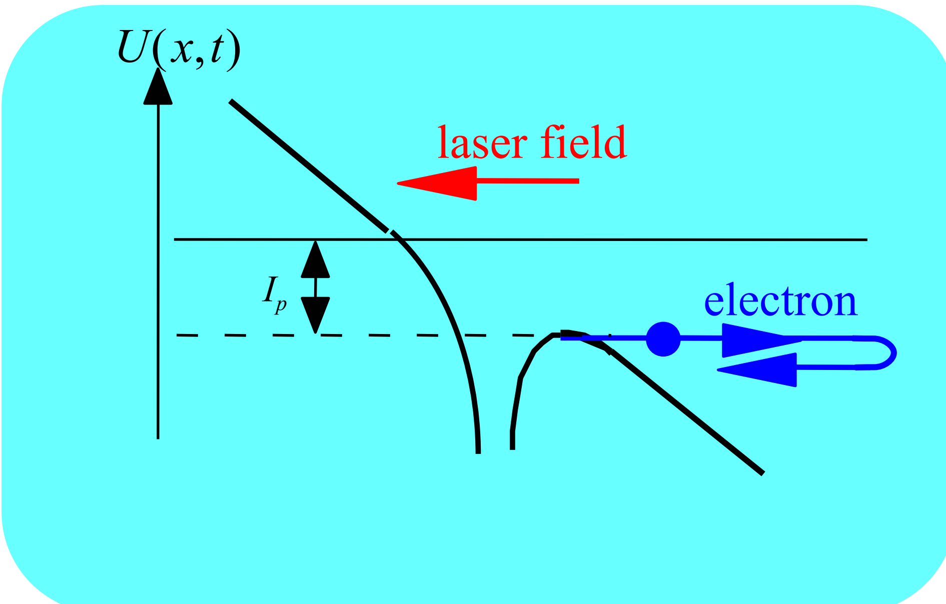






Spatial coherence at 30nm

Harmonics are generated by atoms being ripped apart

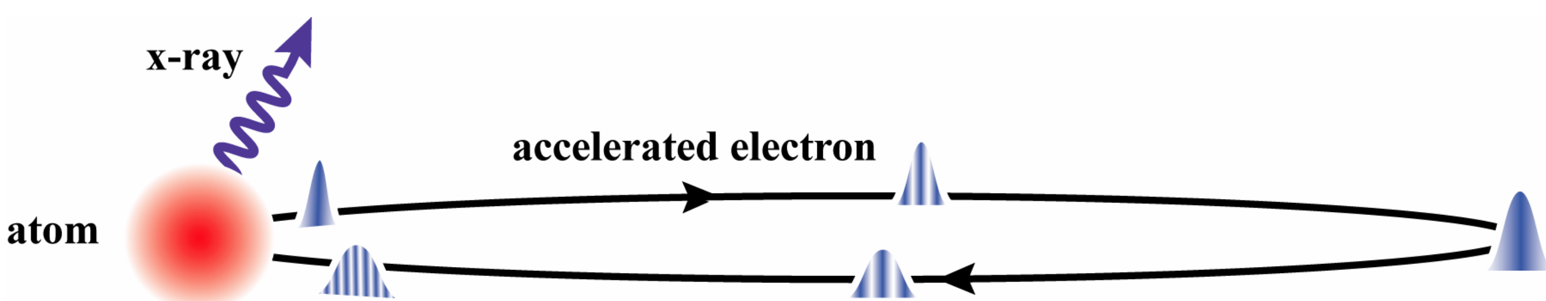


$$h\upsilon_{cutoff} = I_p + 3.2U_p$$

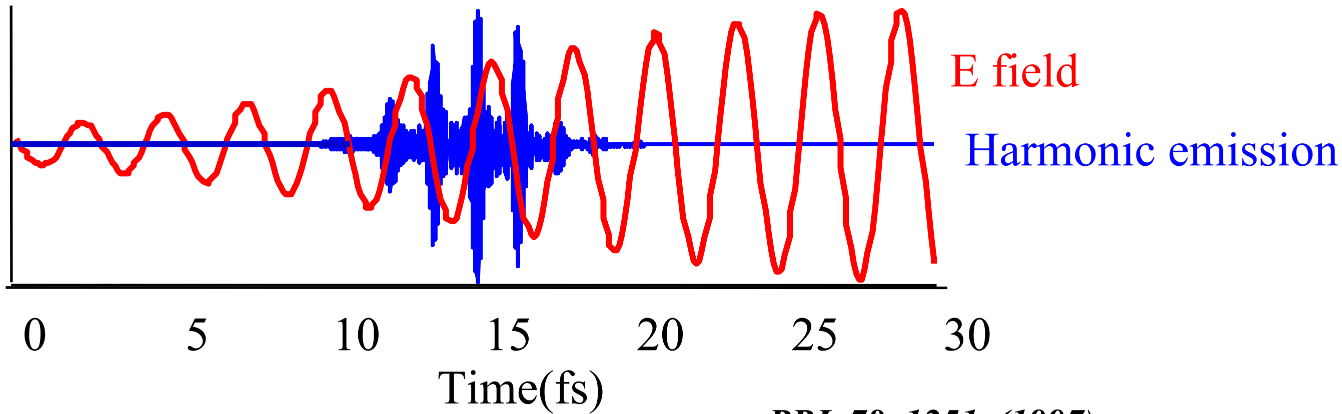
ionization potential of atom

$U_p\ \alpha\ I_s\,\lambda^2$

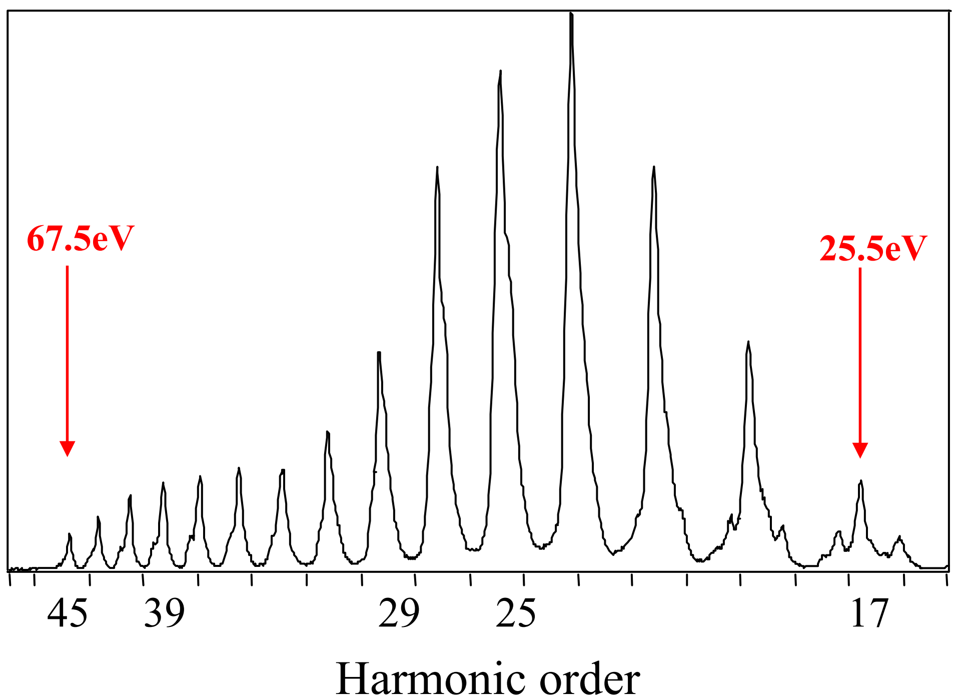
quiver energy of e^-



Periodic emission in time and frequency



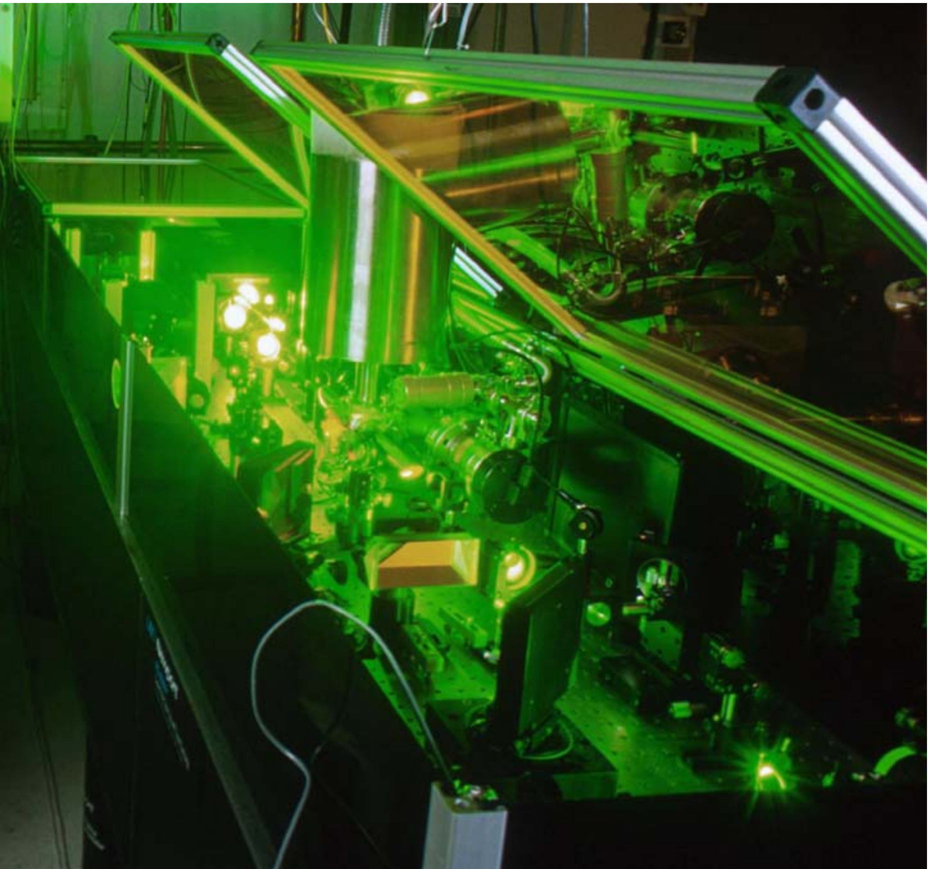
PRL 78, 1251, (1997)

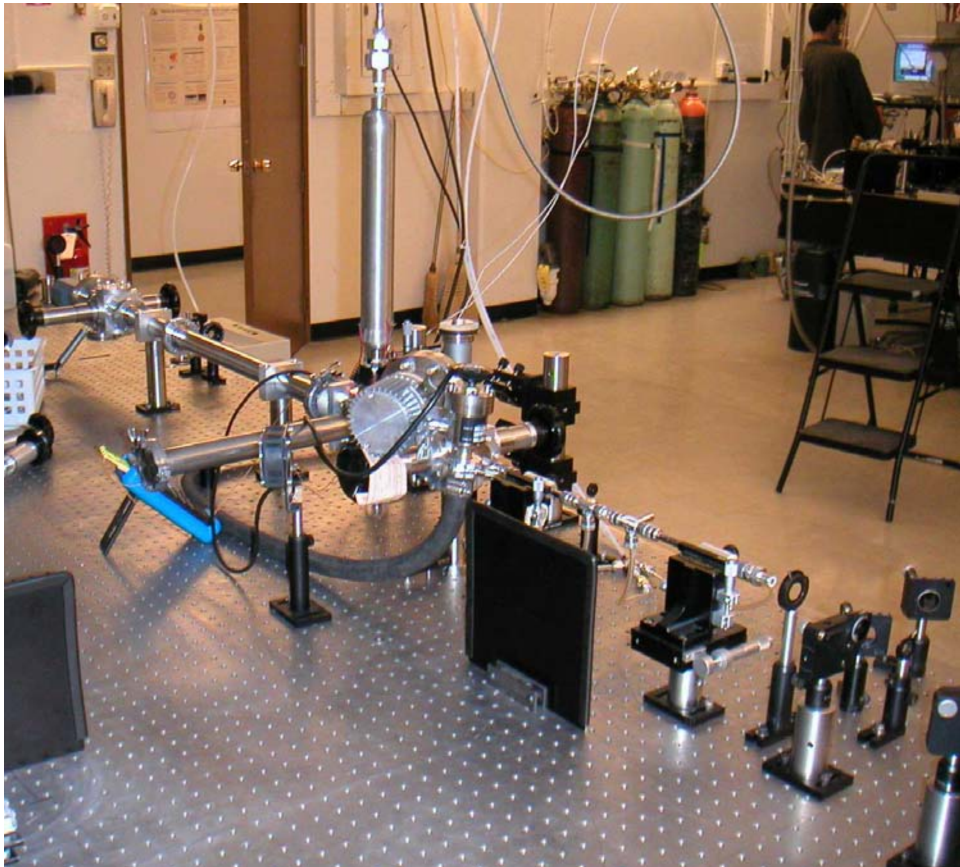


500eV

Compact EUV source from HHG

- **By late 1990s, short-pulse, mJ, kHz lasers became available, allowing for HHG with compact lasers and extending range to 2.7nm (> 500eV)**
- **Applications in surface science, plasma imaging** (Haight, Salieres, Leone, KM group)
- **Controlled phase matching became possible**





History of high harmonic generation

- **EUV harmonics ≈ 38nm observed by Reintjes et al. in 1977** (JOSA 67, 251 (1977))
- **EUV harmonics ≈ 15nm observed by Rhodes et al. in 1987** (JOSA B4, 595 (1987))
- **Initial experiments used 20mJ, multi-table-top lasers at 2-10Hz**

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High-Order Harmonic Generation Using Intense Femtosecond Pulses

J. J. Macklin, J. D. Kmetec, and C. L. Gordon III
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
(Received 21 September 1992)

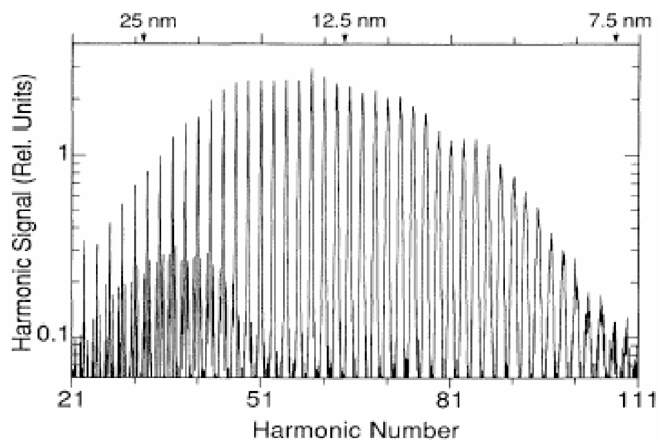
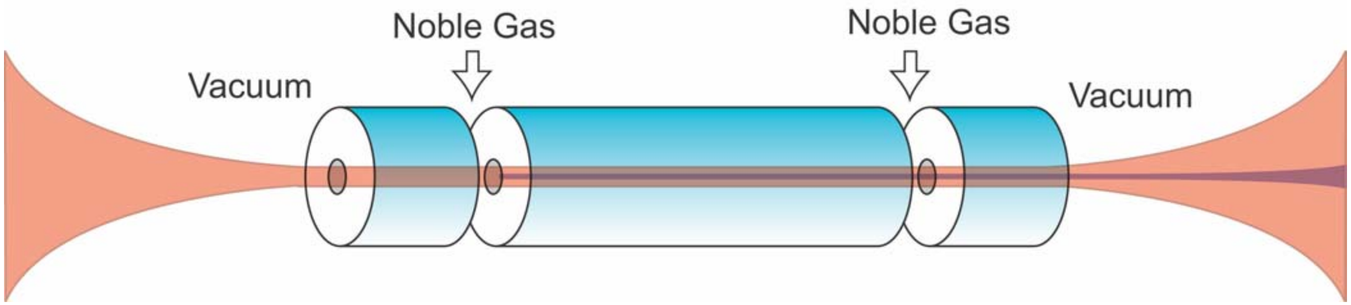
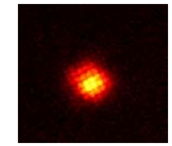


FIG. 4. Harmonic spectrum at 1.3×10^{15} W/cm^2, for 13 Torr of Ne in a 2.5-mm tube. The features running through the low harmonics are high harmonics appearing in second order of the monochromator grating. The spectral width of individual harmonics is instrument limited.

Efficiency < 10^{-7}

Why use hollow fibers?





Phase matching!
Science ***280****, 1412 (1998)*

laser

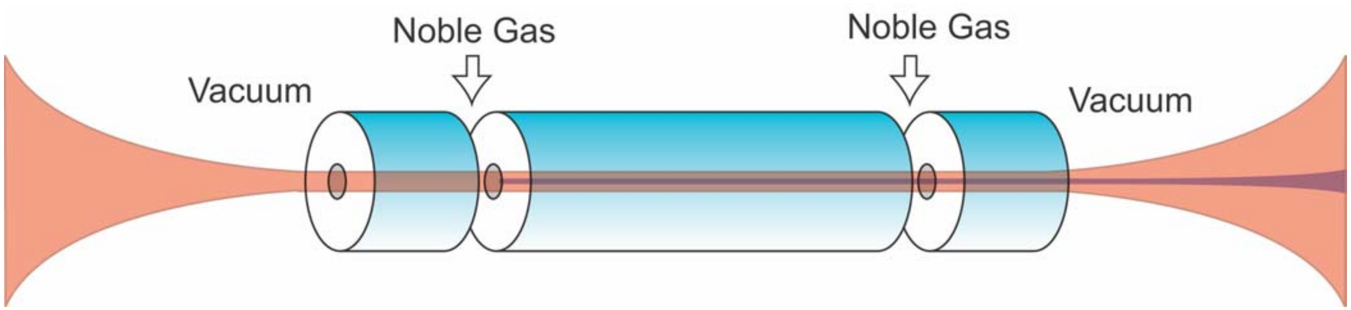
EUV

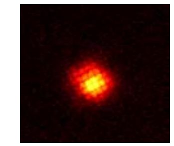
$$k=\frac{2\pi}{\lambda}\left(1+P\delta(\lambda)-\frac{1}{2}\left[\frac{u\lambda}{2\pi a}\right]^{2}-\frac{1}{2}\frac{N_e r_e \lambda^{2}}{\pi}\right)$$

vacuum **gas** **waveguide** **ionization**

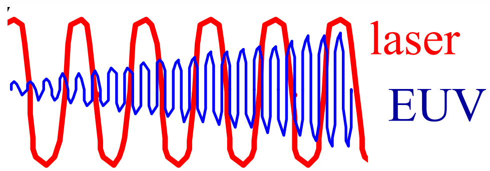
- **Phase matching and long interaction length in fibers increases the** ***efficiency*****, improves the EUV mode** ***beam quality*** **and reduces the** ***gas load***
- **Works well up to 80eV**

Limits of hollow fiber phase matching





Phase matching!
Science ***280****, 1412 (1998)*

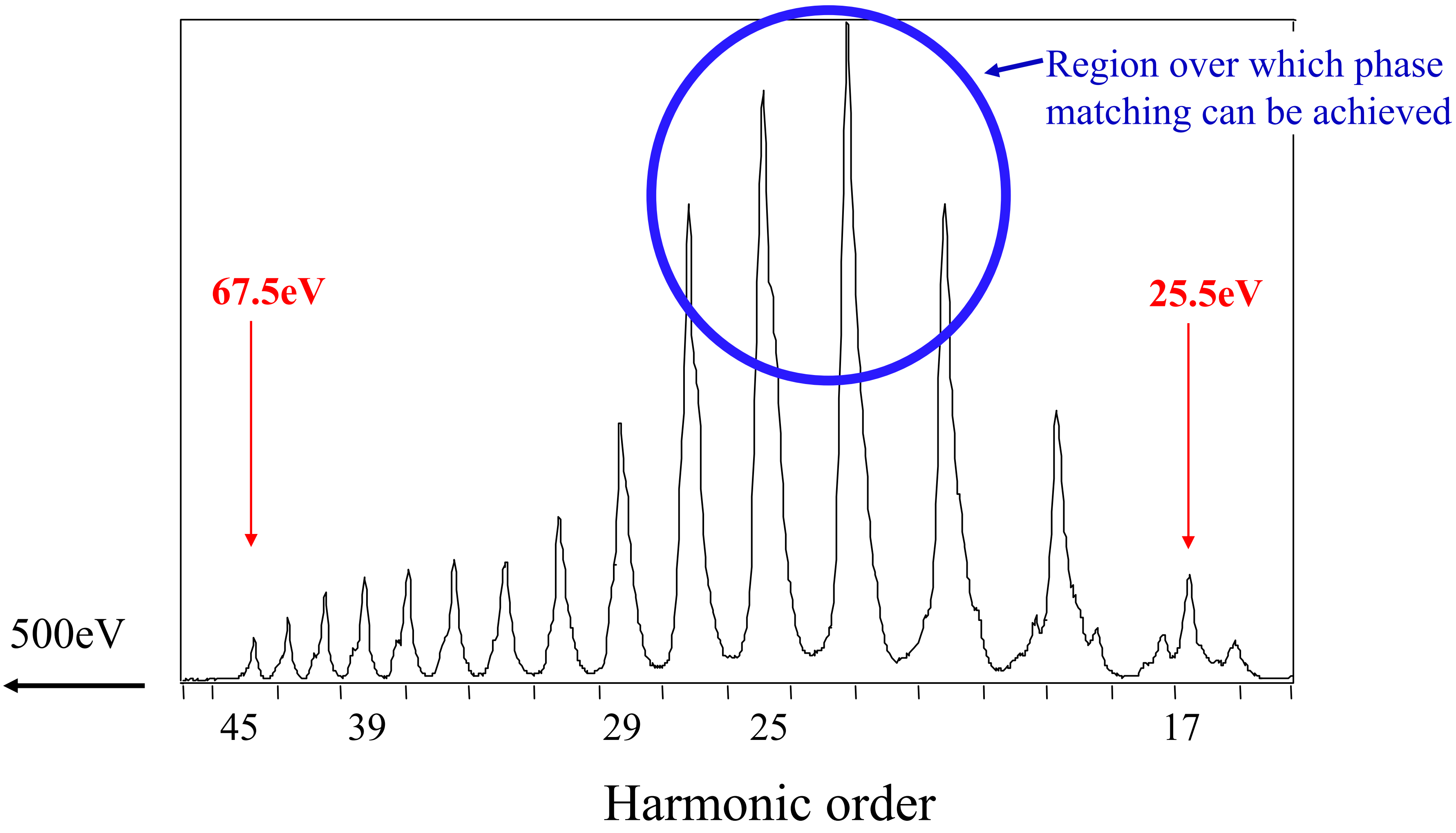


$$k = \frac{2\pi}{\lambda}\left(1 + P\delta(\lambda) - \frac{1}{2}\left[\frac{u\lambda}{2\pi a}\right]^2 - \frac{1}{2}\frac{N_e r_e \lambda^2}{\pi}\right)$$

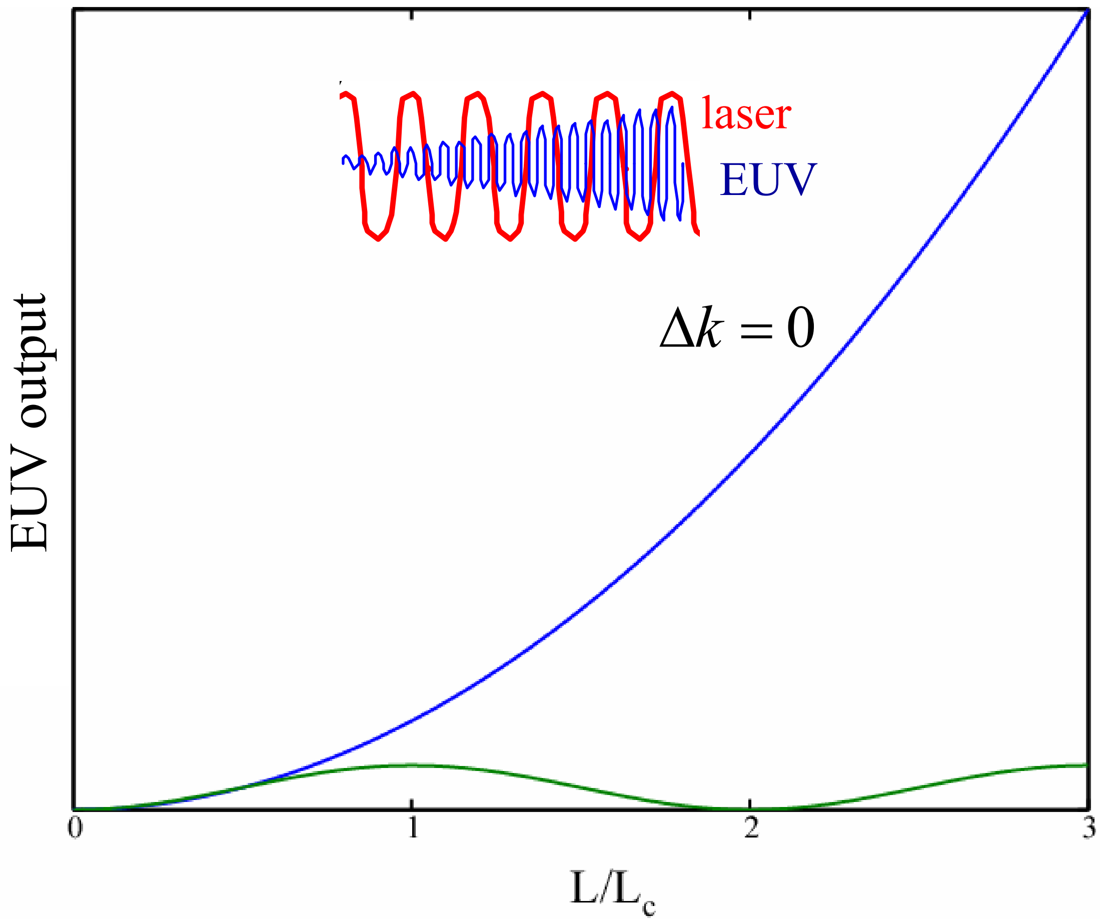
vacuum **gas** **waveguide** **ionization**

Higher harmonics are generated at higher laser intensities and higher levels of ionization => very difficult to generate HHG efficiently above ≈80eV or ionization > 5%

Low pressure HHG spectrum in argon



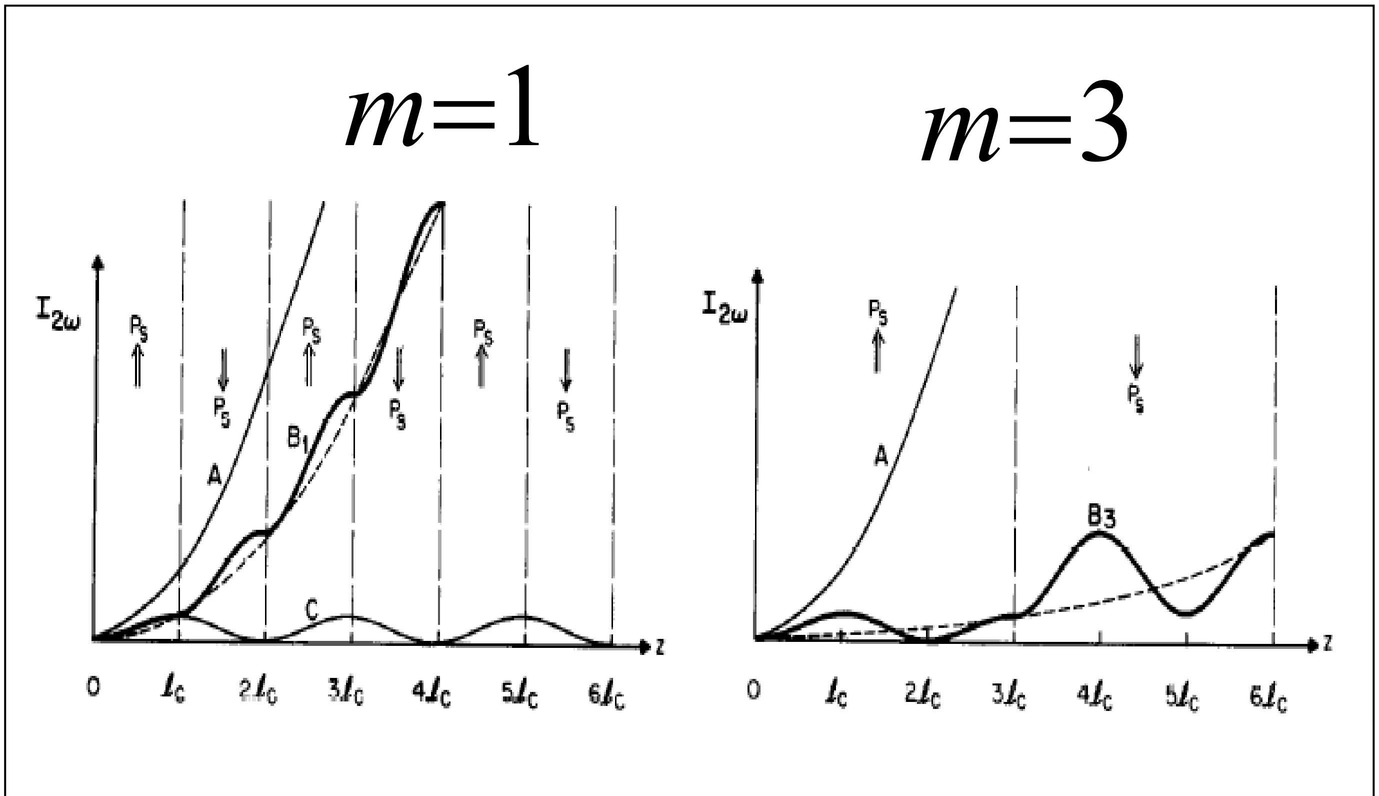
Phase matched signal growth

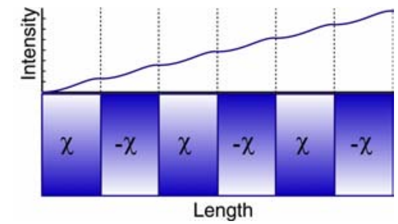


- **Need to phase match to get efficient EUV generation i.e. $qk_{laser} - k_{EUV} = \Delta k = 0$**
- **If $\Delta k \neq 0$, want to adjust or restrict emission from regions that are out of phase**
- **Coherence lengths for HHG in the presence of high levels of ionization are < 100µm**

Quasi-Phase-Matching can adjust for phase mis-match

- Traditional Quasi-Phase-Matching, $\Delta k = K_m = \dfrac{2\pi m}{\Lambda}$ $\quad\Lambda$= Periodicity of nonlinear medium

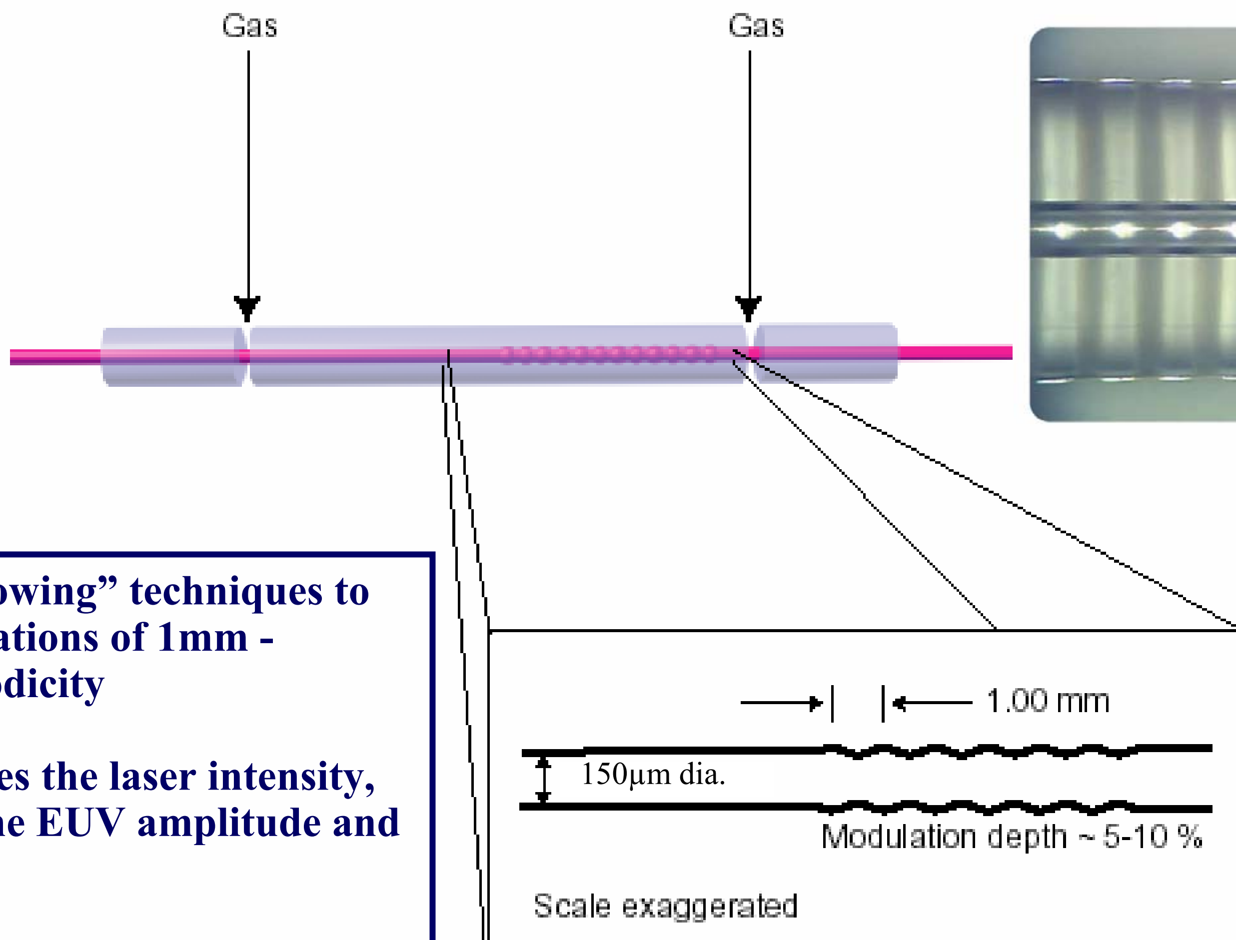


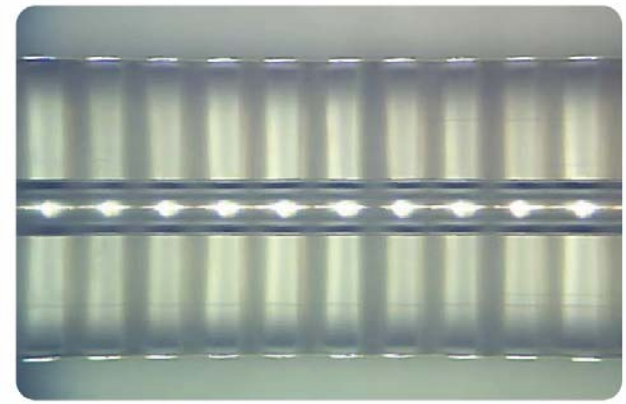


Periodically poled materials

Fejer et al.,JQE ***28****, 2631 (1992); Opt. Lett.* **22**,1834 (1997)

EUV Photonics: modulated hollow core fibers



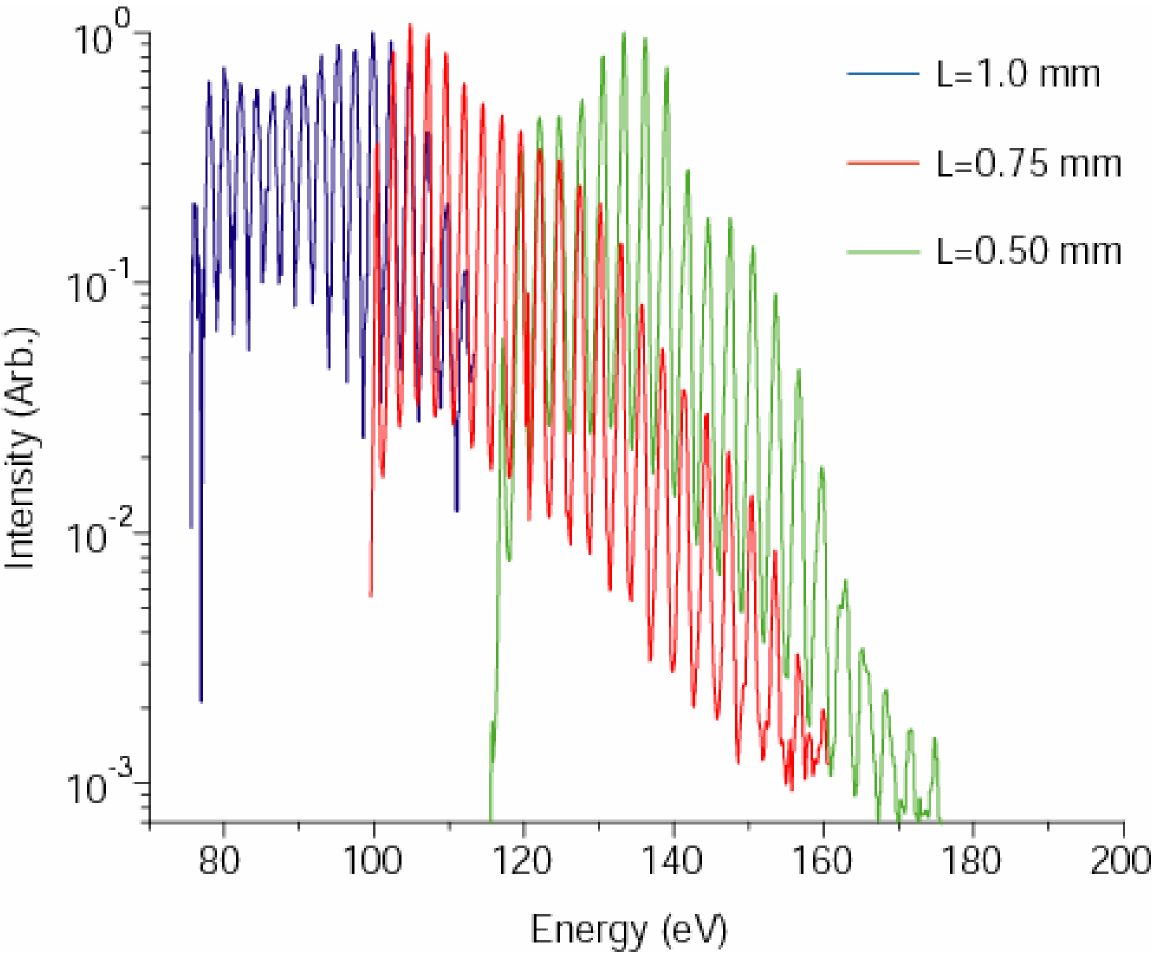


Use "glass-blowing" techniques to create modulations of 1mm - 0.25mm periodicity

This modulates the laser intensity, and in turn the EUV amplitude and phase

Coherence lengths ≈ 10's - 100's microns

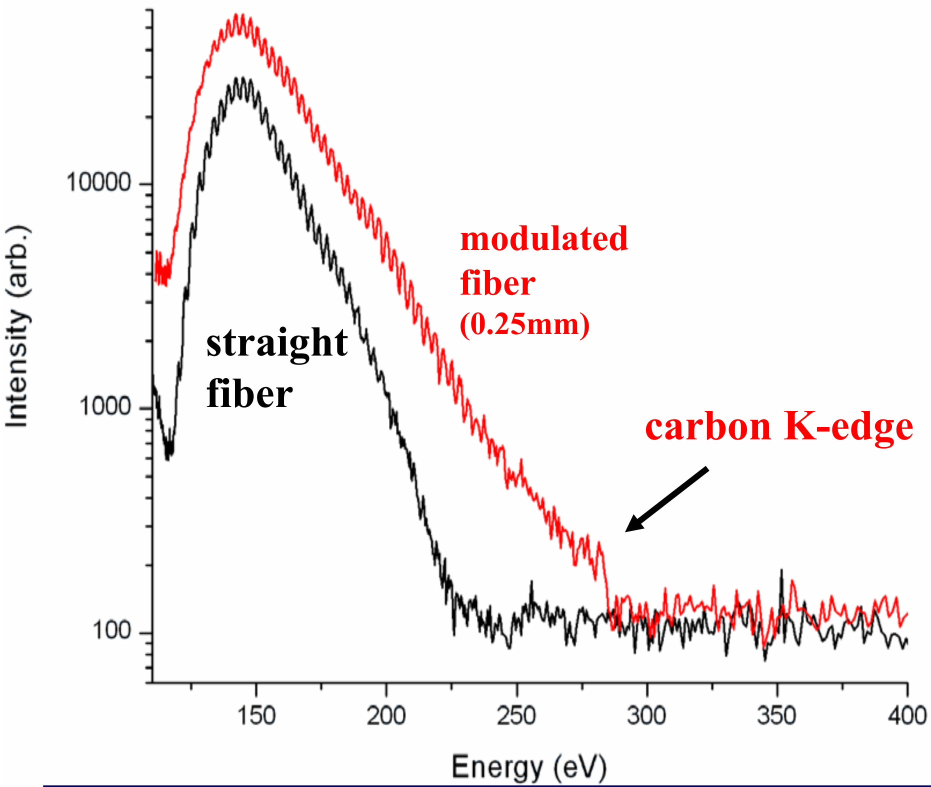
Shorter modulation periods give > 100eV higher energy!

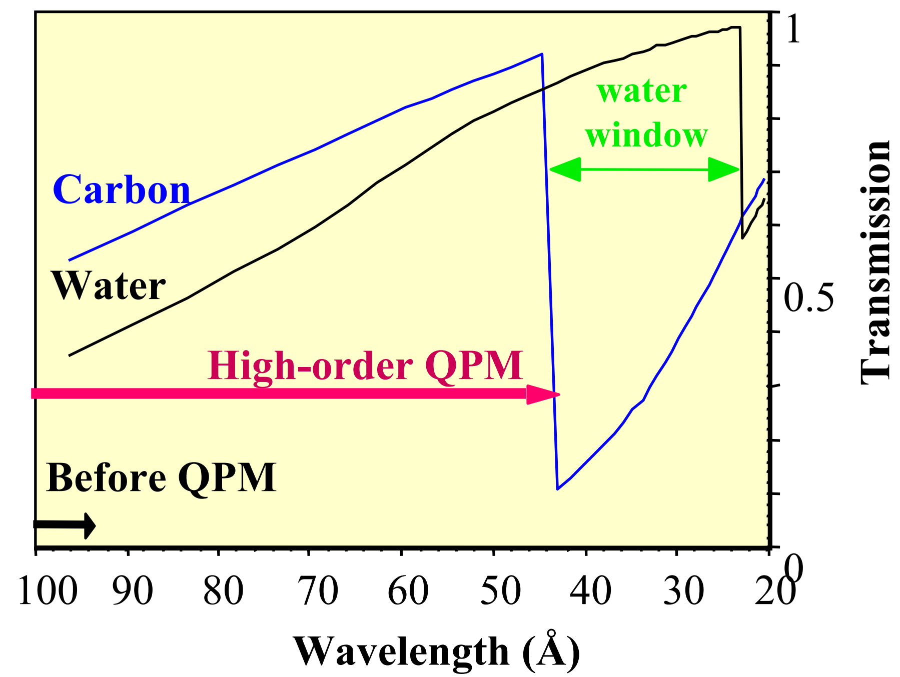


- Cutoff limited by laser intensity
- HHG at ≈ keV possible

Nature ***421***, *51 (2003)*

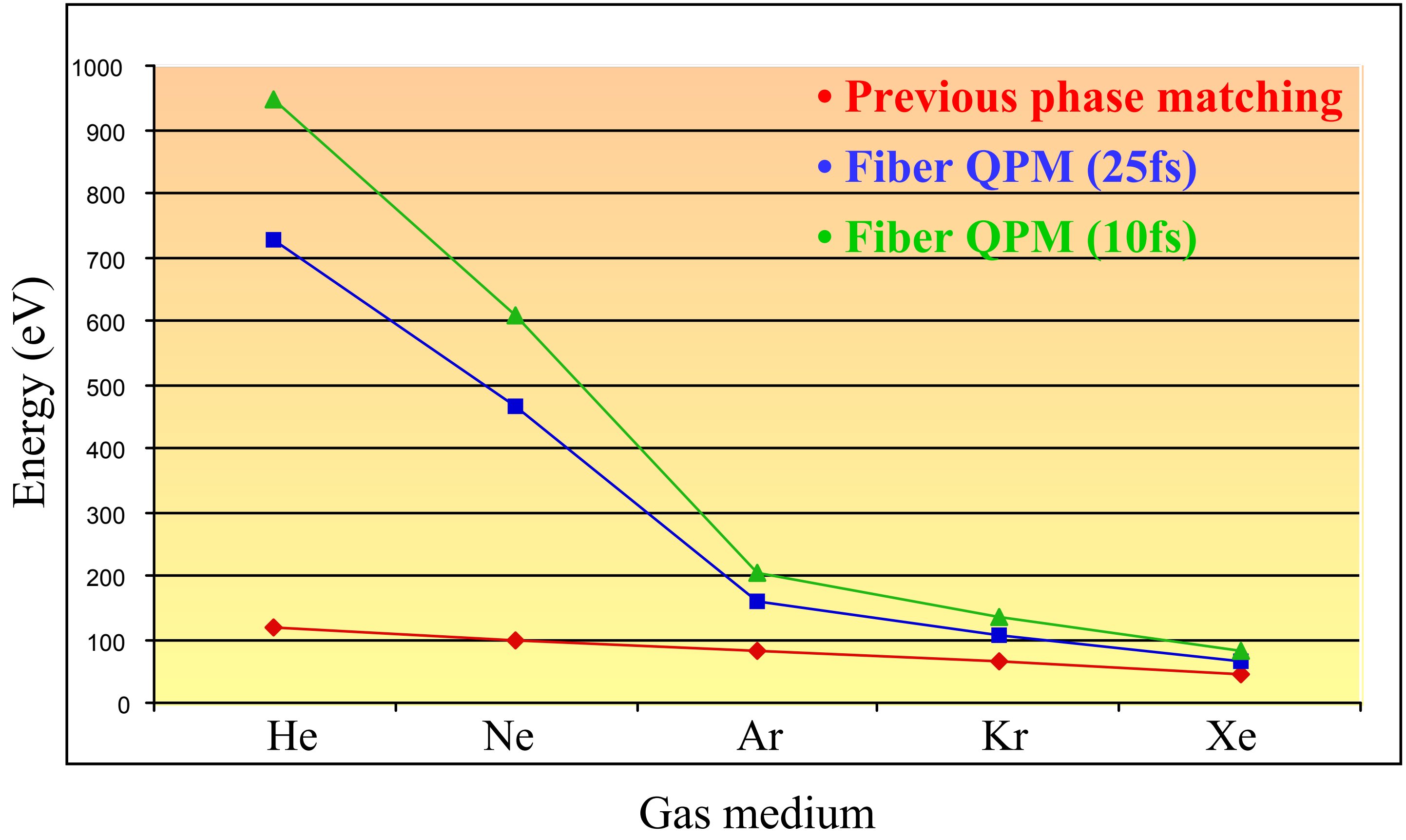
Quasi phase matching of EUV light in the water window in Ne





- **First phase matching technique at ≈ 100% ionization (***Emily Gibson et al., Science* ***302****, 95 (Oct. 2003)*)
- **Clear pathway to increase flux by several orders of magnitude using longer fibers, tighter modulations and higher fields**
- **HHG has promise as a light source up to keV, for chemical spectroscopies and high-contrast bio-microscopies in "water window"**

QPM will significantly extend the efficient range of HHG



Specific routes towards improved EUV HHG sources

- **Increase efficient energy range from 80eV to ≈ keV on a desktop -**

  - modest increase in intensities from 10^{15} Wcm^{-2} to < 10^{16} Wcm^{-2}

  - decreased periodicities and use of tapered fibers (e.g. Λ = 0.1mm)

  - harmonic generation from ions

  - decreasing laser pulsewidth from 20fs to 10fs

  - alternate QPM schemes using colliding pulses

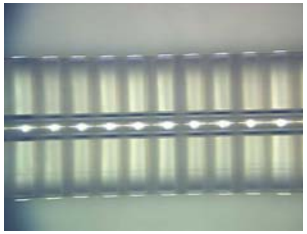
  - higher rep rate lasers and optimized fibers (length, diameter, modulation depth, chirp) will increase flux

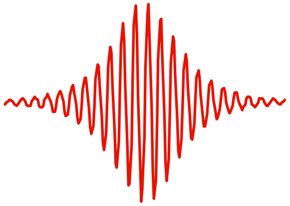
  - coherently rotating molecules may allow us to optimize recollision probability

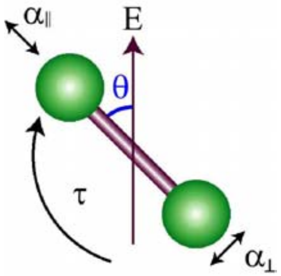
  - using shorter wavelengths to drive HHG

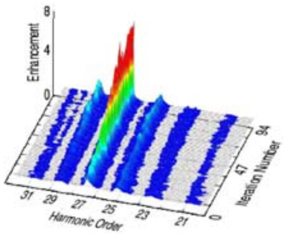
  - designer pulses will channel laser energy into a single harmonic

  - appropriate vision of quantum electronics in the 21st century, involving precise control and manipulation of atoms and molecules

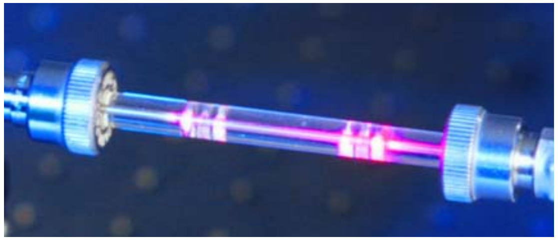








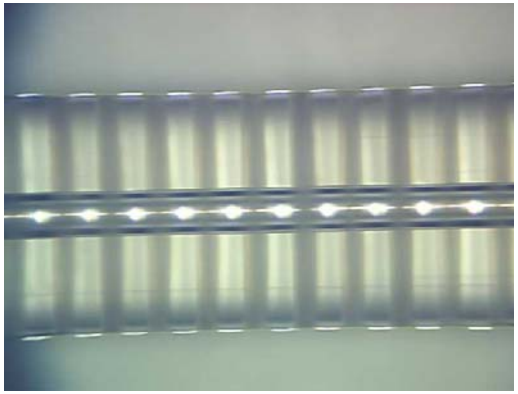
EUV HHG present and future



Straight Fiber

Current EUV HHG sources (per harmonic)**:**

- Pulse Energy: <1nJ @ 2kHz
- Average Power ≈ 2μW at 27nm
- Peak Power : 0.2 MW
- Pulsewidth : < 5 femtoseconds
- Wavelengths : 300nm - 11nm
- Fully spatially coherent
- < Tabletop



Modulated Fiber

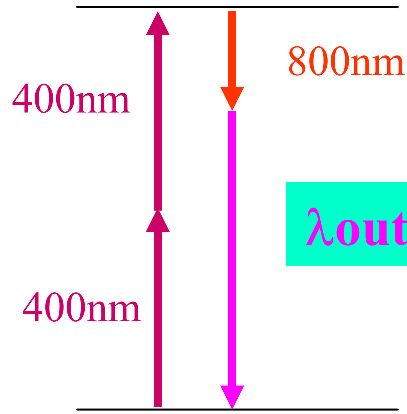
Future EUV QPM sources (per harmonic)**:**

- Pulse Energy: 10nJ @ 20-100kHz
- Average Power ≈ 1mW
- Peak Power : 2 MW
- Pulsewidth : picosecond - attosecond
- Wavelengths : 300nm - 1nm
- Fully spatially coherent
- < Desktop

Why EUV?

Four-Wave Mixing

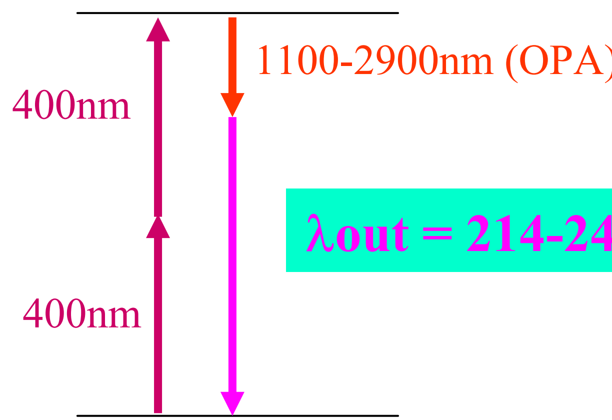
$$2\omega_{\text{pump}} - \omega_{idler} = \omega_{out}$$



λout = 267nm

Four-Wave Mixing

$$2\omega_{\text{pump}} - \omega_{idler} = \omega_{out}$$

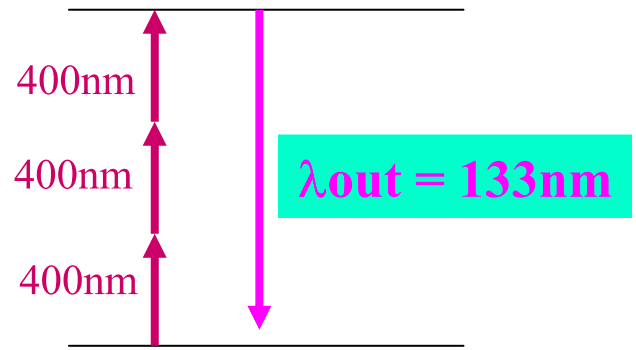


λout = 214-244nm

Why EUV?

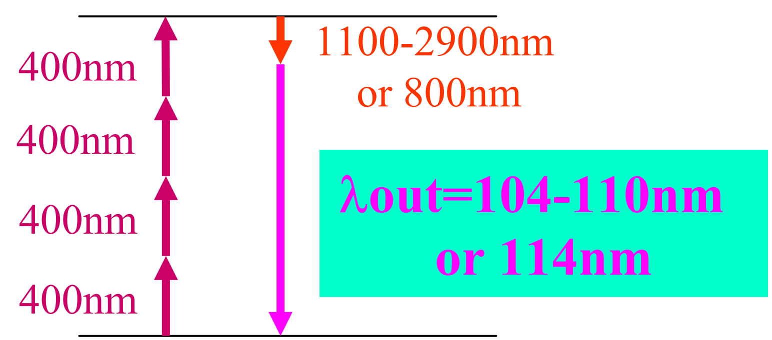
Third-Harmonic Generation

$$3\omega_{\text{pump}} = \omega_{out}$$

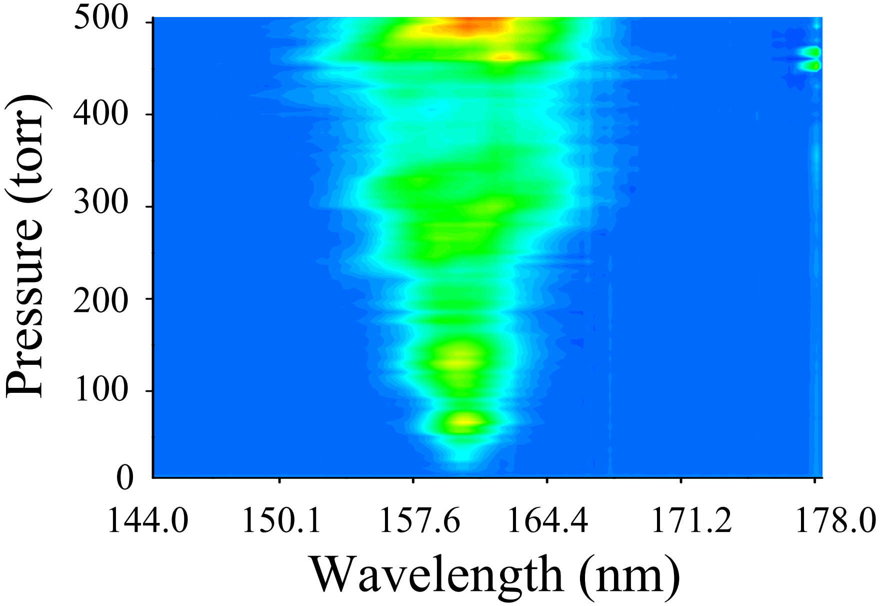


Six-Wave Mixing

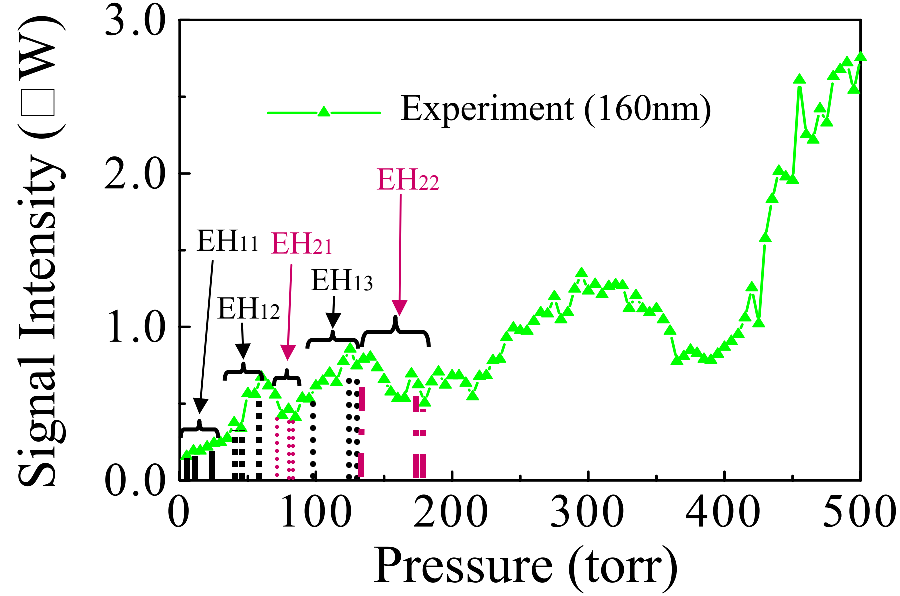
$$4\omega_{\text{pump}} - \omega_{idler} = \omega_{out}$$



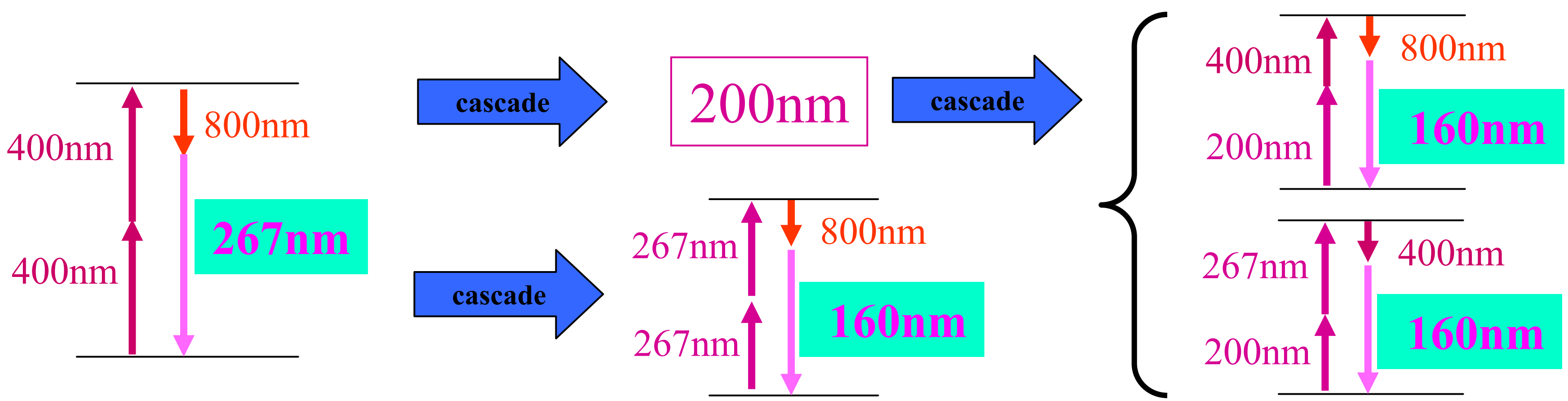
Why EUV?



500
400
300
200
100
0
Pressure (torr)
144.0
150.1
157.6
164.4
171.2
178.0
Wavelength (nm)

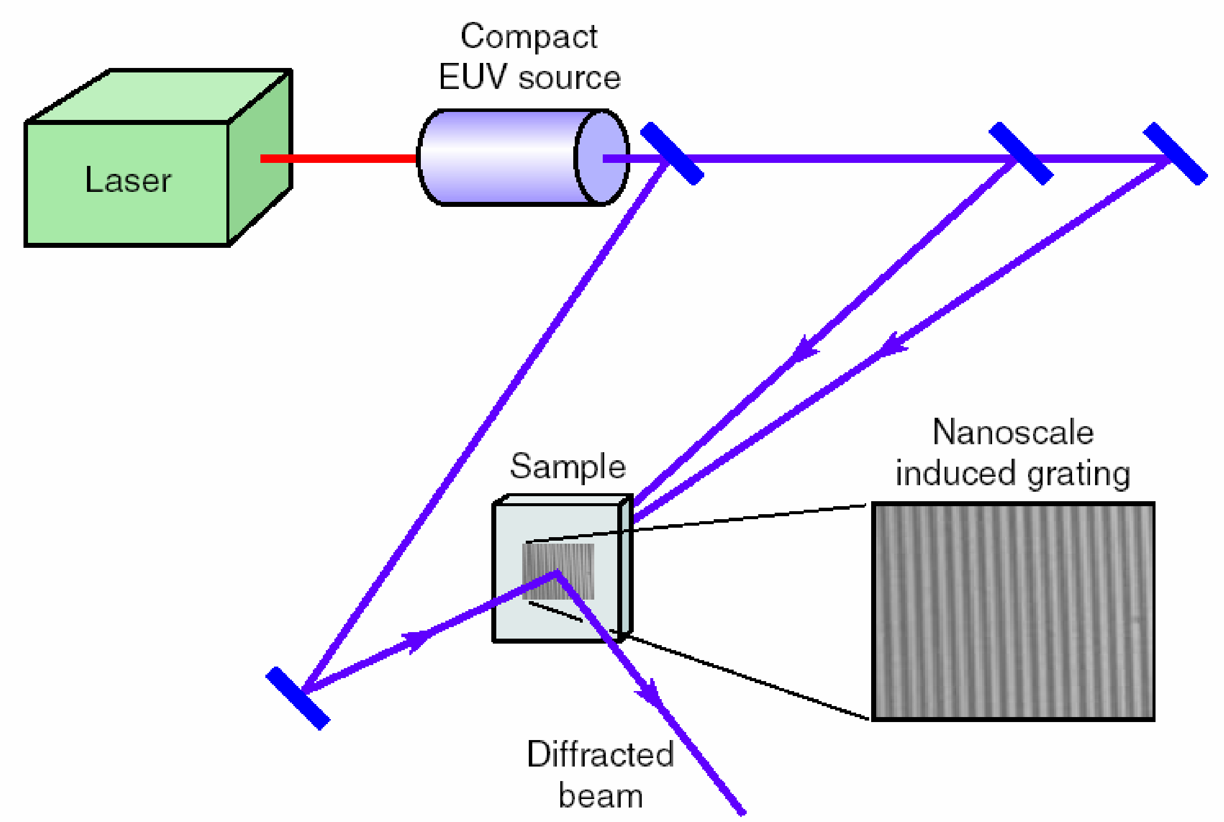


3.0
2.0
1.0
0.0
Signal Intensity (□W)
Experiment (160nm)
EH11
EH12
EH21
EH13
EH22
0
100
200
300
400
500
Pressure (torr)

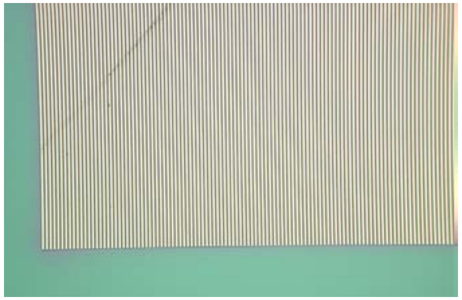


400nm
400nm
800nm
267nm
cascade
cascade
200nm
cascade
267nm
267nm
800nm
160nm
400nm
200nm
800nm
160nm
267nm
200nm
400nm
160nm

EUV Nonlinear spectroscopies

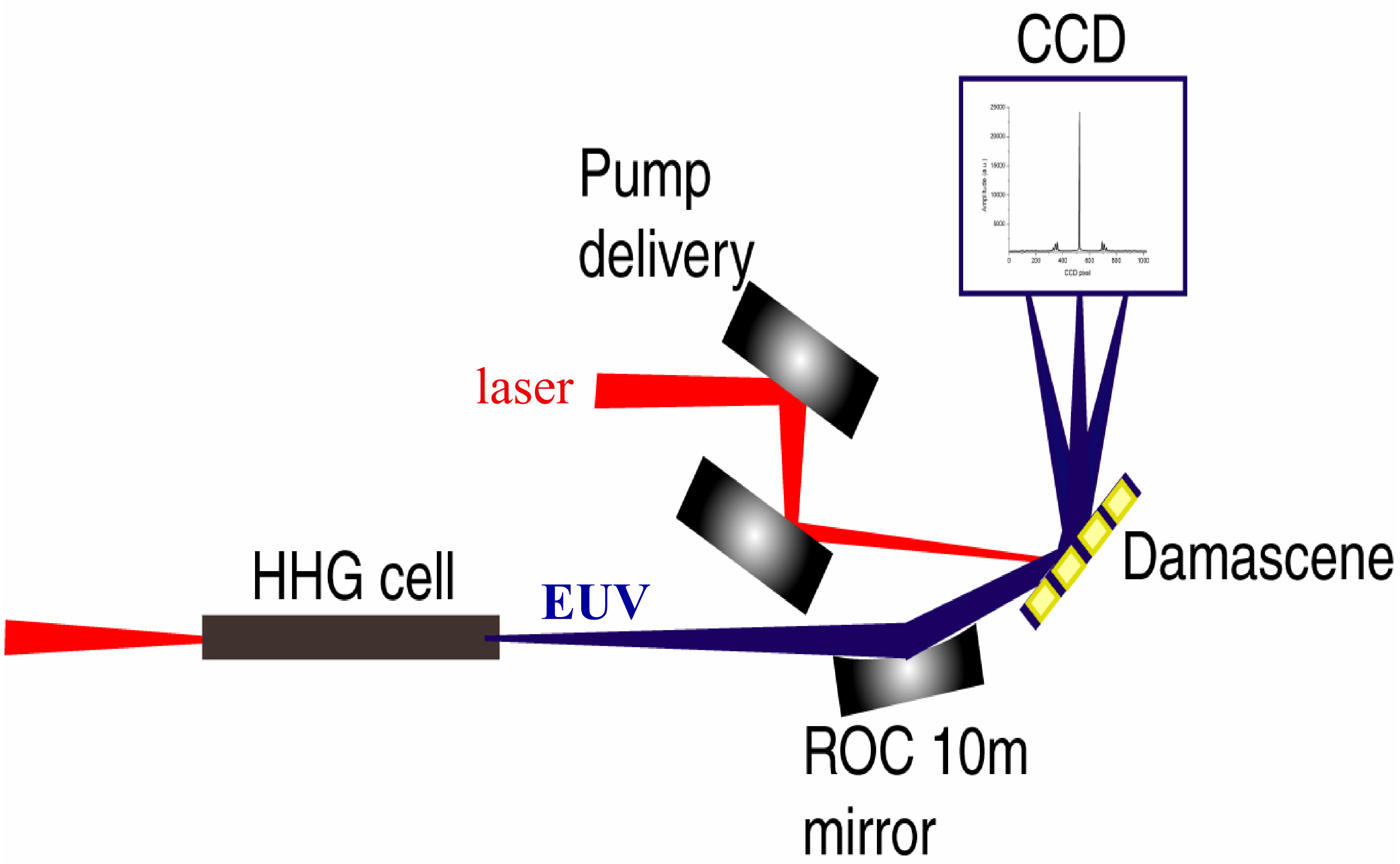


EUV nonlinear spectroscopies for measuring nanometer-scale ultrafast thermal and electronic responses of materials

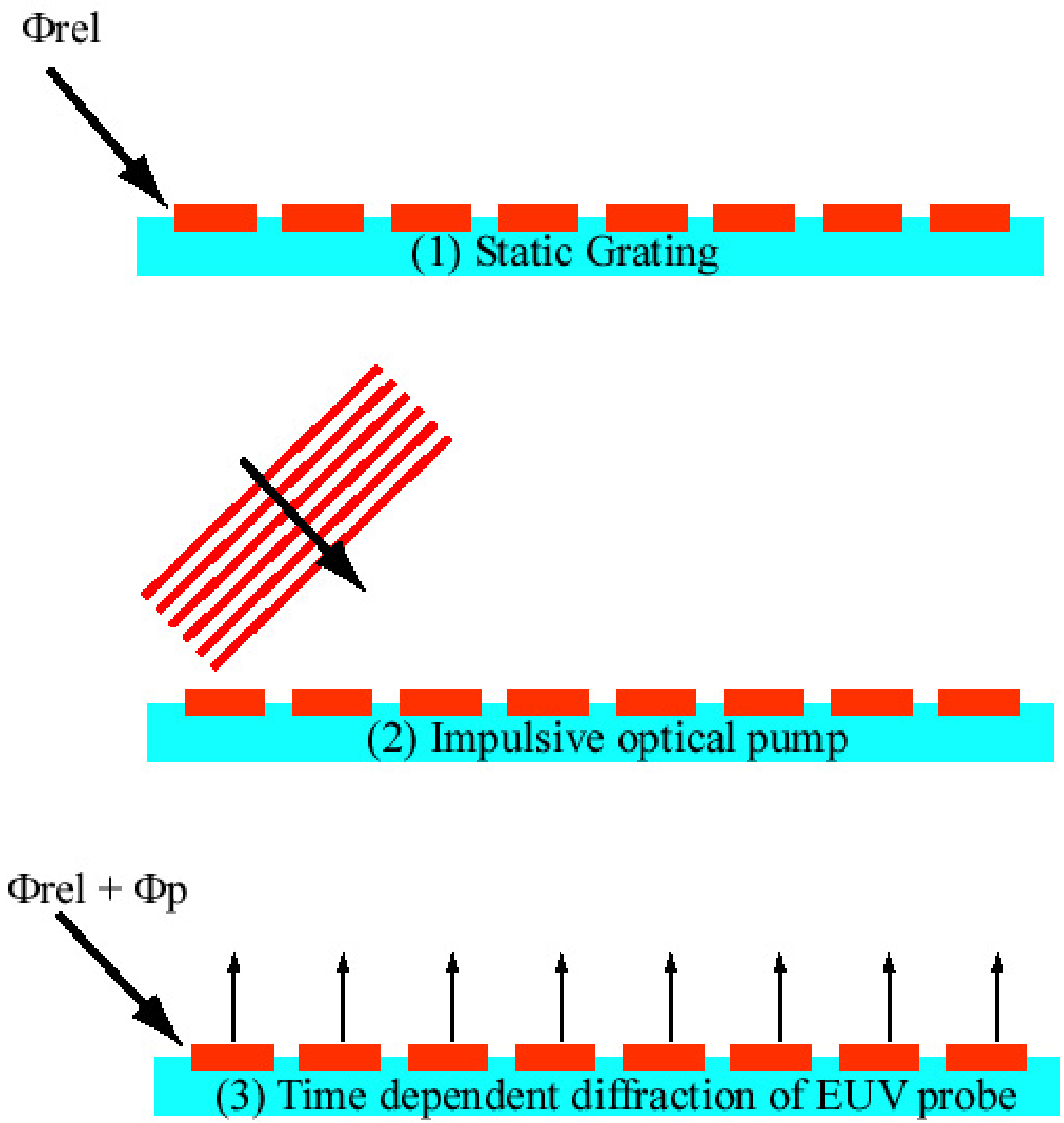


Damascene grating with alternate silicon and copper stripes

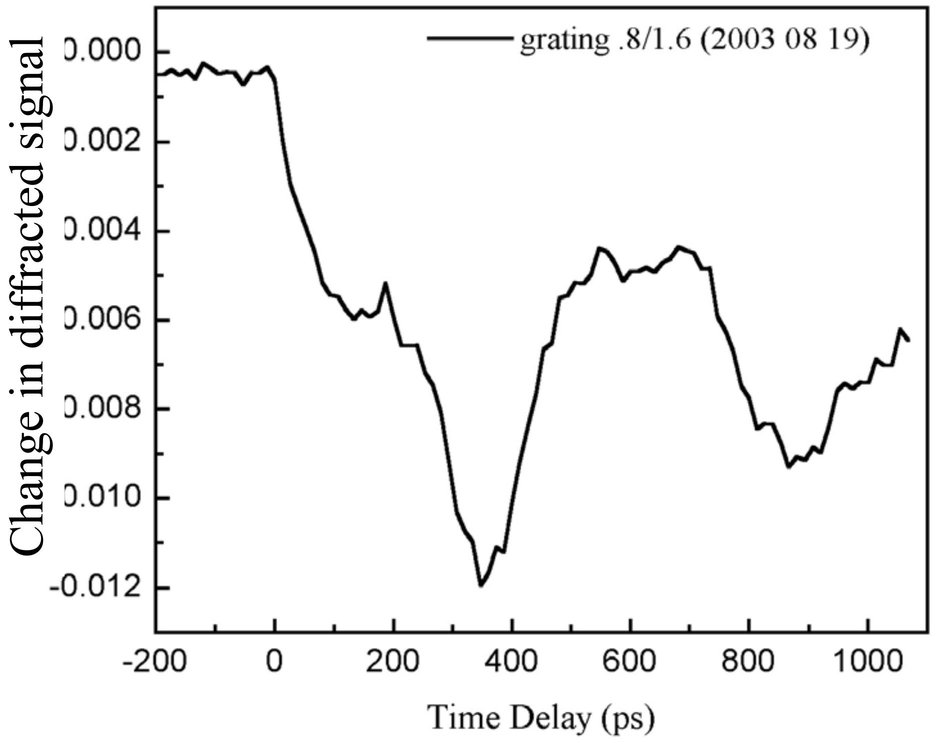
Experimental Setup

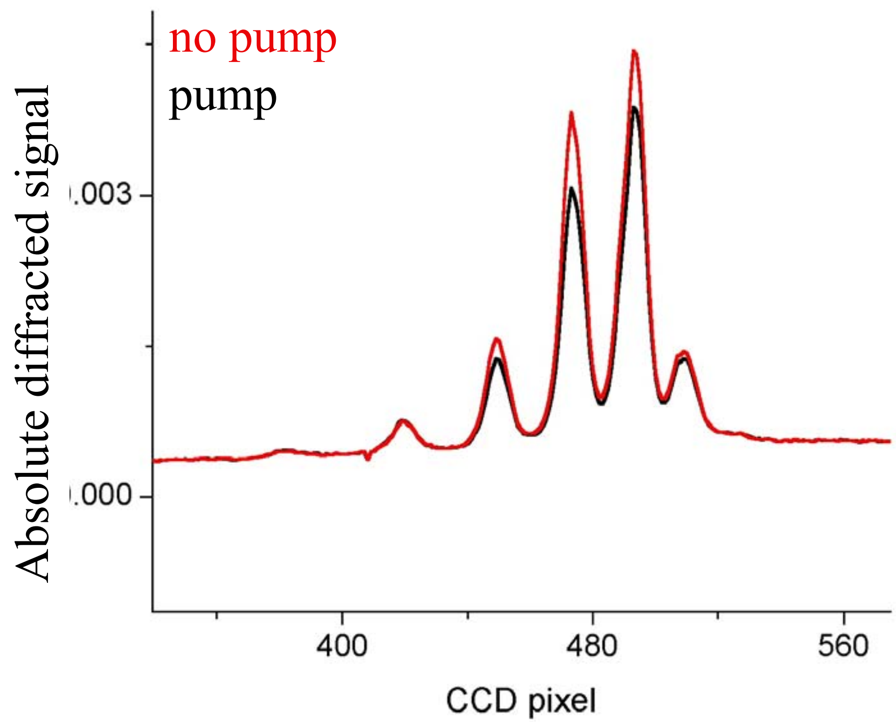


Impulsive Stimulated Thermal Scattering

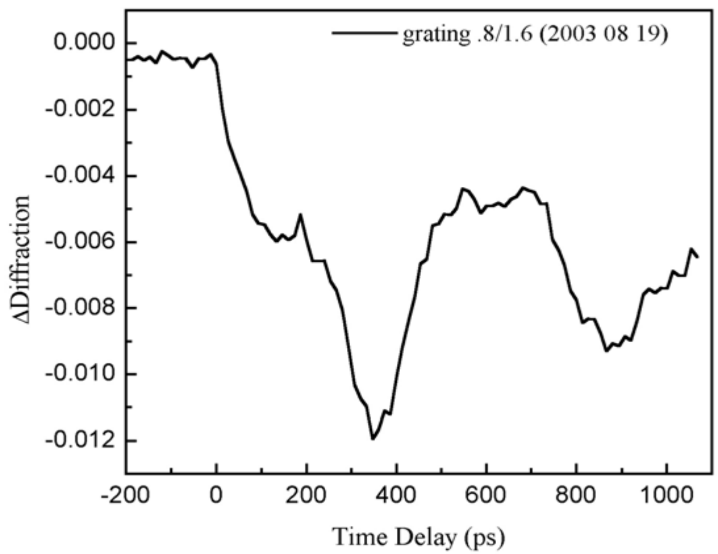


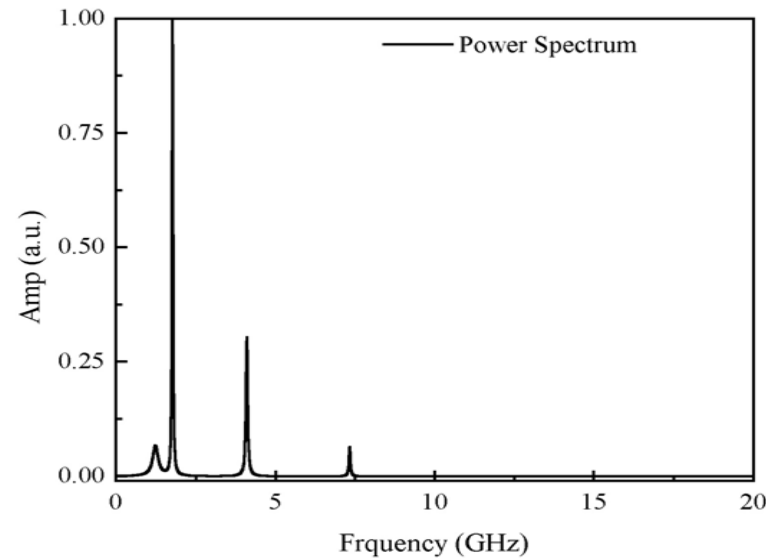
Observe strong experimental EUV modulated signal

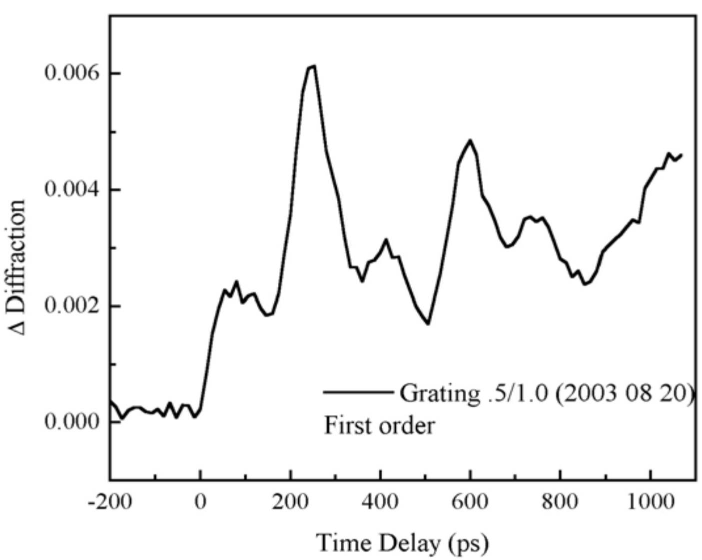


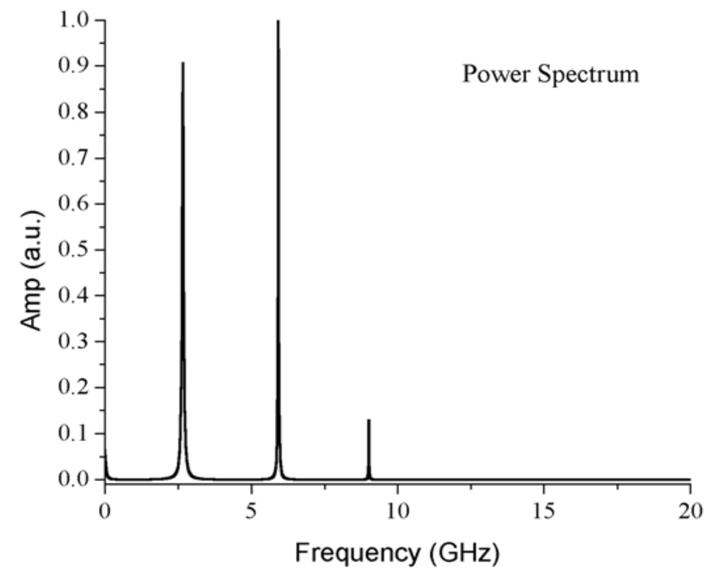


Filter diagonalization yields power spectrum









Theory (cont'd)

- **Changes in diffraction efficiency:**

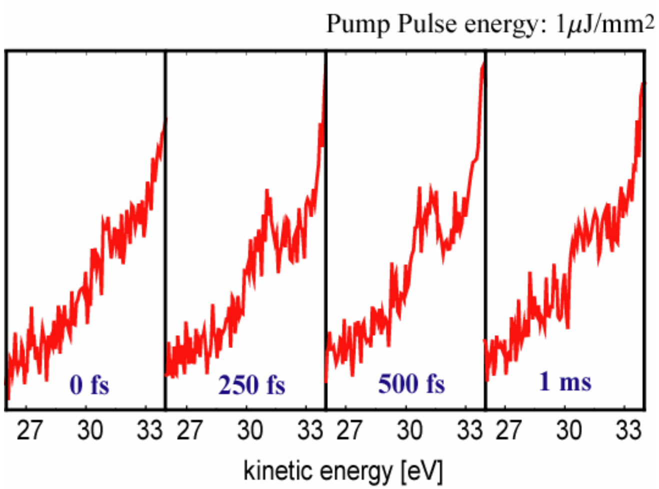
$$\frac{\left|C_n\right|^2 - \left|C_n^{pumped}\right|^2}{\frac{1}{2}\left(\left|C_n\right|^2 + \left|C_n^{pumped}\right|^2\right)}$$

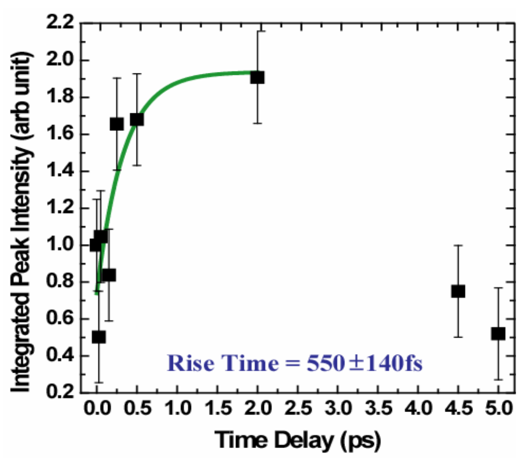
- **The observed changes in reflectivity of several percent are in agreement with theory, assuming a .3nm relative change in height. This deflection was independently verified using interferometry for similar experimental conditions.**

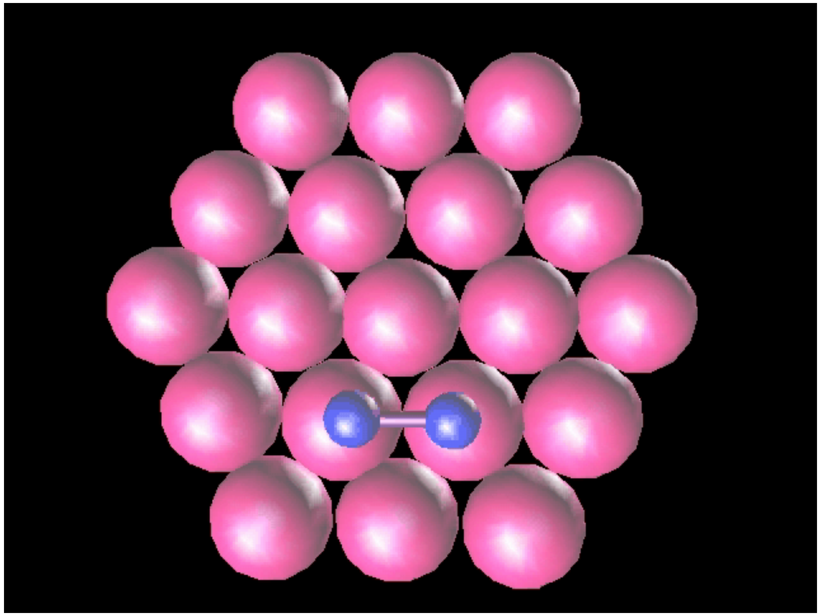
Future work:

- Use smaller scale structures
- Understanding temporal structure
- Examine different overcoated materials
- Perform transient grating expt. using multiple beams

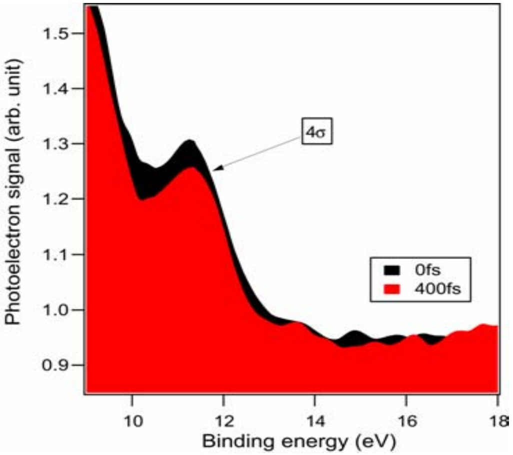
Oxygen motion on Pt surface:

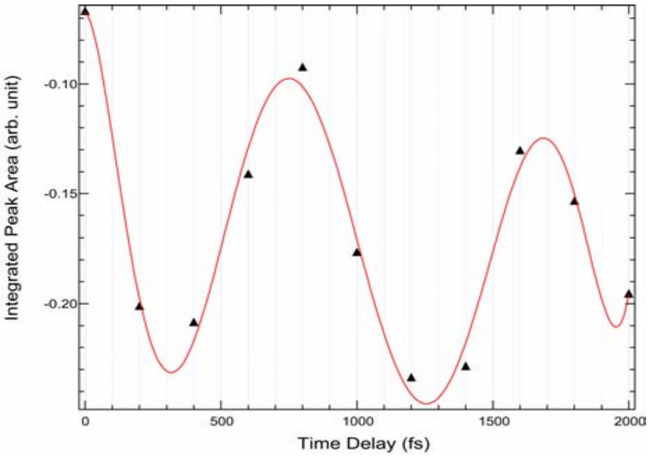


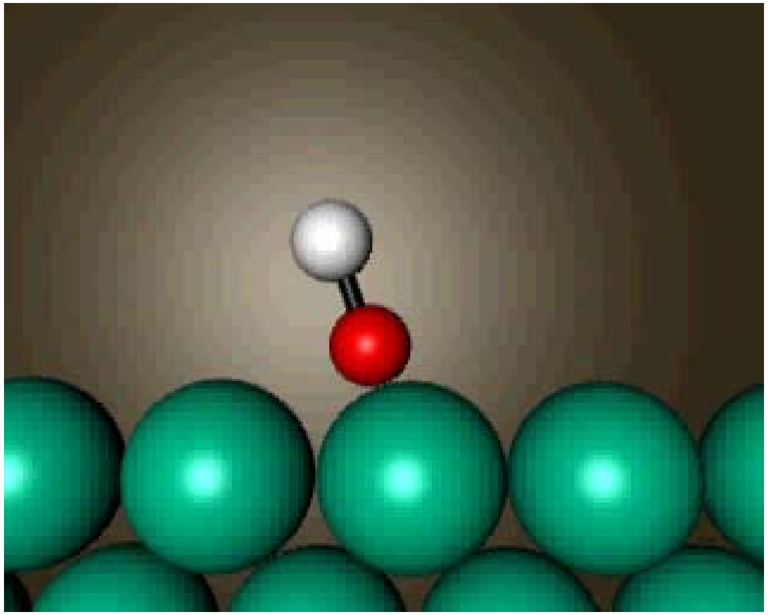




CO oscillation on Pt surface:







Conclusion

- **“Laser-like” coherent beams in EUV**
  - **full spatial coherence** *(Science **297**, 376 (2002))*
  - **full temporal coherence** *(Nature **406**,164 (2000))*
  - **EUV photonics** *(Nature **421**,51 (2003))*

- **Advances limited only by our imagination**
  - **compact EUV light sources over sub-keV energy range**
  - **new linear and nonlinear spectroscopies**
  - **nano and element-specific microscopies**
  - **compact imaging systems**

- **Strong, coordinated, effort abroad**
  - **EU consortia (Imperial College, Lund, FOM, ETH Zurich, Vienna, Max Born, Max Plank, Italy, Greece, France)**
  - **Large new consortium in Canada for basic/applied intense fields**
  - **Several laboratories in Japan with large facilities in EUV laser**